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BRECCIA AT SUDBURY, ONTARIO*

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ABSTRACT

Field and laboratory study of structural breccia in the vicinity of Sudbury indicate the following sequence of events during the post-Huronian deformation which produced it. Aqueous fluids at elevated temperature and pressure permeated strikewise fractures along which there was slight dislocation of the walls. Fragments were torn loose and comminution was aided by action of the fluids. This formed a mobile matrix which in time attained sufficient volume to transport the remaining fragments. Low confining pressure permitted easy movement of the breccia and prevented the development of good crystallographic orientation in the minerals. The magmatic fluids enriched the matrix particularly in sodium and in general increased the amounts of mica, chlorite, sodic plagioclase, etc., over that found in the fragments. Study of three breccia types shows a tendency for the matrixes to converge toward a common chemical composition. Following these changes came the introduction of nickeliferous sulphides, unimportant in most breccia bodies, but locally giving rise to ore bodies such as the Frood.

INTRODUCTION

Breccias associated with the pre-Cambrian sediments and igneous rocks at Sudbury have been known for many years and are described briefly in almost all published reports on the district. They occur south of the norite intrusive for the most part and extend undetermined distances east and west of the city of Sudbury. They are im-

* Published by permission of the Provincial Geologist, Department of Mines, Toronto, Ontario.

portant because of their association with the nickel ore bodies, the Frood mine being the most notable example now operating. Recent study by H. J. Fraser[1] of "ore breccia" related to the Frood deposit and by T. C. Phemister[2] of nonmineralized "rock breccia" to the south provided the impetus for the investigation reported in the following pages. In the summer of 1939 the writers mapped for the Ontario Department of Mines selected areas of rock breccia by plane table on a scale of 400 feet equals 1 inch. In the laboratory the chemical and structural petrology was studied in some detail. The description and interpretation of this work is the topic of this report.

GENERAL GEOLOGY

The major geological features at Sudbury are too well known to require detailed description. A. B. Yates[3] has outlined recently the latest authoritative opinion concerning the rocks associated with the ores, and H. W. Fairbairn[4] has discussed the relation of the Sudbury and Bruce sedimentary series. Reference to earlier work by Collins, Burrows and Rickaby, Coleman, etc., will be found in these papers. It is sufficient here to summarize the geological relations (Table 1). Breccia occurs extensively in a number of the formations listed, but of these only the Ramsay Lake, Mississagi, and the Sudbury gabbro formations have been studied in detail. Figure 1, of McKim Township, shows the location of most of the breccia mapped by the writers. It centers in the Ramsay Lake formation and overlaps into the adjacent gabbro and Mississagi. Although there is abundant breccia elsewhere, this particular belt was selected because of confusion experienced by previous workers in separating conglomerate of the Ramsay Lake formation from associated breccias. This difficulty has been a very real one because of the rounding of most breccia fragments and their superficial resemblance to true conglomerate boulders. Fairbairn[5] has described misinterpretations of this kind.

[1] "Petrology of Sudbury Norite and Footwall Rocks" (unpublished report to International Nickel Co., 1937).

[2] Unpublished report to Ont. Dept. Mines, 1937.

[3] "The Sudbury Intrusive," *Trans. Roy. Soc. Can. Sec. IV*, Vol. XXXII (1938), p. 151.

[4] "Sudbury-Bruce Series Relations, etc.," *Bull. Ont. Dept. Mines*, Vol. L (in press).

[5] *Ibid.*

The breccias follow in general the regional strike of the horizons in which they occur. In detail, however, they consist of irregular patches of crushed rock which have no apparent pattern. In places

TABLE 1

GEOLOGICAL COLUMN AT SUDBURY

Post-Huronian		Late sulphide mineralization
		Faulting. Local brecciation of olivine diabase
		Olivine-diabase dikes
		Trap dikes
		Main sulphide mineralization
		Faulting and brecciation
		Small trap and aplite dikes
		Quartz-diorite "offset" dikes
		Granite (M)—Murray and Creighton types
		Norite and "micropegmatite" (N)
		Gabbro (G)—(may be pre-Whitewater)
		Intrusive contact
Huronian	Whitewater series	Chelmsford grit
		Onwatin slate
		Onaping tuff
		Unconformity (?)
	Cobalt series	Lorrain quartzite
		Gowganda formation
		Unconformity (minor)
	Sudbury-Bruce series (SB)	Serpent quartzite
		Espanola formation (graywacke and limestone)
		Bruce conglomerate and quartzite
		Mississagi formation (quartzite and argillite)
		Ramsay Lake formation (grit, conglomerate, quartzite)
		McKim formation (graywacke and quartzite)
		Copper Cliff rhyolite
		Fault contact (and probable unconformity)
Pre-Huronian		Sediments and volcanic schists (includes Frood series, etc., but is not yet completely subdivided)

* For discussion of this late mineralization and brecciation of olivine diabase see authors' report, "Breccia at Sudbury," *Bull. Ont. Dept. Mines* (in press).

sharp bends occur and the breccia zone may intersect the bedding at high angles. The fragments are predominantly those of the rock in which the brecciation has occurred. Fragments foreign to the host-rock are also found, but their source is usually evident. Subangular to rounded fragments are the rule rather than the exception. The matrix is invariably finer grained than the fragments and commonly

shows a rude foliation. This foliation is due to parallelism of platy minerals, chiefly mica, and to compositional banding shown by alternate mica-rich and mica-poor layers.

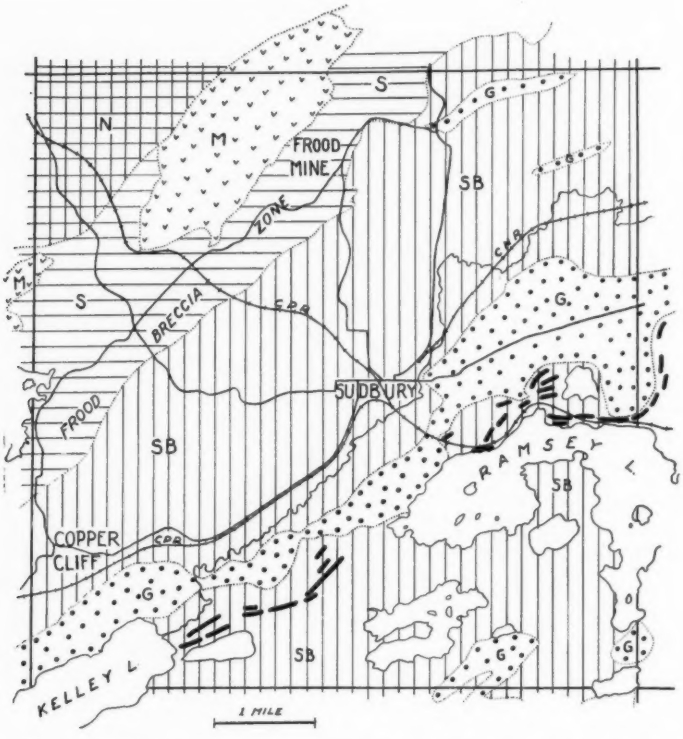

FIG. 1.—Geological relations of the breccia in McKim Township. Principal breccia areas examined are shown in heavy solid lines. *N* = norite, *M* = Murray granite, *S* = pre-Huronian schists, etc., *G* = gabbro, *SB* = Sudbury-Bruce series.

Brecciation occurred at a late date in the pre-Cambrian history of Sudbury. It antedates the olivine diabase and is later than the quartz-diorite "offsets." A description is given on a later page of brecciation in olivine diabase which may be of the same origin as that in the older rocks. The evidence is inconclusive. In the case of

the brecciated quartz diorite studied by Fraser,[6] replacement of the matrix by nickel-bearing sulphides has produced the Frood ore body, one of the largest in the world. Similar ore breccias occur in the Creighton, Levack, and other less important deposits. The barren rock breccias investigated by the writers contain only minor amounts of sulphides but are similar in character in all other respects. These rock breccias will now be discussed in more detail.

FIELD AND PETROGRAPHIC DESCRIPTION

CLASSIFICATION OF THE BRECCIAS

For purposes of discussion the rock breccias at Sudbury are classified as (1) vein and stockwork breccias, (2) contact breccias, and (3) injection breccias.

Vein and stockwork breccias occur entirely within a single formation. An intricate network of veins may extend continuously for hundreds of feet, or a single narrow vein may be the only evidence of brecciation. The walls of some veins are straight, but commonly they show irregularities and embayments. The matrix of the vein breccia varies in width from one-quarter inch to 2 feet. In places it contains many fragments of the wall rocks. Few of these are more than 1 foot in diameter, but fragments 5 feet in diameter have been found. Breccia containing numerous large fragments may be called stockwork breccia. Although most of the fragments in vein and stockwork breccias are of local origin, fragments of other formations are rarely absent. Most of these originate in formations older than the formation which is host to the breccia. The weathered matrix is noticeably of a different color from the fragments, is finer textured, and is commonly marked by very fine lines parallel to the vein wall. Near irregularities in the walls these lines show swirls and irregular folds. These structures are not easily detected except on weathered surfaces.

Breccia formed at the boundary of two formations is called contact breccia. The fragments are large, ranging usually from 1 to 5 feet in diameter. Larger ones 200–400 feet long have been mapped (Fig. 2). In the breccia associated with the Frood deposit Yates[7]

[6] *Op. cit.*

[7] *Op. cit.*, p. 169.

describes a fragment 2,600 feet long and 900 feet wide. The smaller fragments are usually rounded, the larger ones lenticular. The predominant fragments of contact breccia consist of the two formations in contact, but foreign inclusions are found also as a rule. Although they may derive from any formation in the area, they are usually from horizons older than those involved in the contact brecciation.

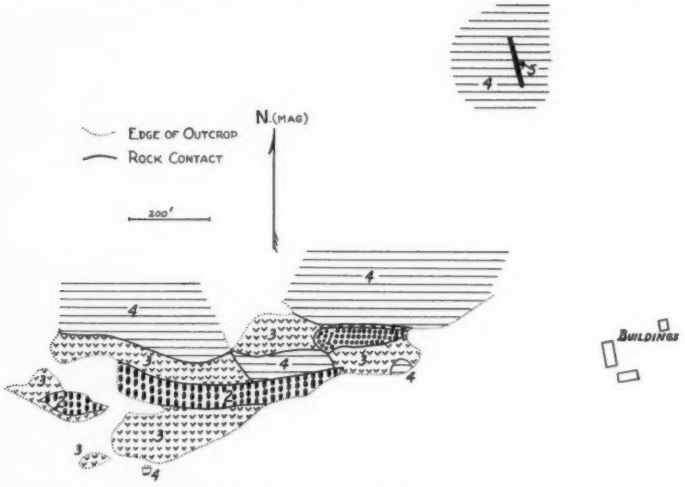

FIG. 2.—Gabbro contact breccia, lots 5 and 6, concession 6, Neelon Township. *1* = Ramsay Lake conglomerate. *2* = Mississagi quartzite. *3* = Mississagi breccia. *4* = Gabbro. *5* = Injection vein in gabbro.

Fragments of rocks not identified in the Sudbury area have also been found. The matrix appears to be comminuted material of the two rocks between which the breccia lies. The color contrast with the fragments and finer textures are features common also to the vein breccias and are equally characteristic.

Injection breccias are composed of a matrix and fragments which are foreign to the host-rock. Breccia of this type occurs both within formations and along contacts. It commonly crosscuts the regional structure in the manner of a true dike intrusion. Its other characters —fine matrix, foliation parallel to walls, etc.—present no feature not already described.

PROPORTIONS OF FRAGMENTS AND MATRIX

The manifold character of the breccia, ranging from matrix veins almost free of recognizable inclusions to stockworks crowded with fragments, makes it difficult to give a reliable average estimate of the volume ratio of the fragments and the matrix. Two calculations have been made using the sketched outcrops of Figures 3 and 4. These

FIG. 3.—Ramsay Lake breccia sketched from an outcrop. Shows typical fragment sizes and shapes, fine flow lines in the matrix, and general northeast orientation. Approximate volume ratio of fragments and matrix is 64:36.

show proportions of fragments and matrix which are probably close to average. In each example the fragments comprise more than one-half the total volume (64:36 for the Ramsay Lake breccia in Fig. 3, and 55:45 for the gabbro breccia in Fig. 4).

VEIN BRECCIA IN THE RAMSAY LAKE FORMATION

The Ramsay Lake formation consists of grit, conglomerate, and quartzite, named in decreasing order of abundance. Its thickness is measured in hundreds, rather than thousands, of feet and is highly

variable. The grit is usually coarse grained, massive, and of a greyish color. Its distinguishing mark is the occurrence of numerous white quartz grains slightly above the average grain size which stand out in relief on weathered surfaces. These white grains, one-eighth inch in diameter and larger, serve to distinguish the Ramsay Lake from the somewhat similar Bruce formation. Microscopically, the grit

FIG. 4.—Breccia in gabbro sketched from an outcrop. Similar to Fig. 3 but shows greater disparity in size of fragments. The flow lines in the matrix and rude parallelism of the fragments indicate an east-west trend. Approximate volume ratio of fragments and matrix is 55:45.

shows an uneven texture of large and small quartz grains. Along the grain boundaries of the quartz is a fine interstitial growth of sericite and biotite. In many of the thin sections there is evidence of a cataclastic texture, probably related to the period of brecciation. A chemical analysis and approximate mode of the grit is included in Table 2. The dominance of quartz and mica in the rock is the most conspicuous mineralogical feature.

Pebbles and boulders of various sizes are scattered throughout the grit but seem more abundant toward the top of the formation.

Granite is the commonest material. On the south shore of Kelley Lake (lot 1, concession 5, Waters Township) a granite boulder 5 feet in diameter is contained in the grit.

TABLE 2

CHEMICAL ANALYSES AND APPROXIMATE MODES

	1	2	3	4	5	6
SiO_2	77.22	77.00	83.91	69.93	50.86	56.31
Al_2O_3	11.27	11.46	9.71	14.30	12.13	14.93
Fe_2O_3	0.99	0.64	0.69	1.89	1.49	0.67
FeO	2.44	2.66	0.77	2.93	5.68	5.09
CaO	0.77	0.81	0.06	0.07	14.10	8.92
MgO	1.29	1.36	0.78	2.52	12.40	8.06
K_2O	3.14	3.07	1.24	4.08	0.52	0.22
Na_2O	0.18	0.40	1.87	2.20	0.84	3.82
H_2O	1.36	1.32	0.58	1.35	1.84	0.99
CO_2	0.15	tr	0.32	0.20	0.57	0.40
TiO_2	0.45	0.47	0.16	0.40	0.34	0.67
P_2O_5	0.07	0.06	0.05	0.07	0.07	0.09
FeS_2	0.47	0.49	tr	tr	.....	0.21
Total	99.80	99.74	100.14	99.94	100.84	100.38
Spec. gr.	2.737	2.808	2.668	2.755	3.000	2.876
Quartz	60	60	65	40	1	5
Biotite	10	10	5	15	5	.....
Sericite and possible kaolin minerals	20	20	20	20	.....	25
Plagioclase	2 (An20)	.....	5 (An30)	20 (An20)	25 (An70)	20 (An5)
Chlorite	×	×	.....	.....	×	.....
Epidote	×	×	.....	×	..	×
Magnetite and iron oxides	×	×	×	×	×	×
Carbonates	× } 8	× } 10	×	× } 5	× } 9	× } 10
Apatite	×	×	× } 5	×	×	×
Rutile and "leucoxene"	×	×	×	×	×	×
Pyrite	×	×	.....	.....	.....	×
Hornblende	.....	.....	.....	.....	60	.....
Actinolite	.....	.....	.....	.....	.....	40

1. Ramsay Lake grit.
2. Ramsay Lake breccia matrix.
3. Mississagi quartzite.
4. Mississagi breccia matrix.
5. Sudbury gabbro.
6. Gabbro breccia matrix.

Analyses 1, 2, 3, 4, and 6 furnished by the Ont. Dept. Mines. Analysis 5 from W. A. Jones, *Univ. Toronto Studies* (Geol. ser. No. 27), p. 67. Specific gravities on bulk samples.

Lenses of massive, gray-white quartzite occur in the Ramsay Lake formation, the largest mapped being 400 feet long and 100 feet wide.

In thin section they show a uniform texture of fine quartz grains with a little interstitial sericite. Most of these quartzite beds have been broken and the fragments rotated during brecciation.

Vein breccia is well developed in the Ramsay Lake formation at many places. A locality on the outskirts of Sudbury on the north shore of Ramsay Lake (lots 3 and 4, concession 3, McKim Township) is typical. The breccia bears an unmistakable resemblance to the grit described above. The matrix is finer grained, more micaceous, and commonly a different shade of gray from the grit but shows consistently on weathered surfaces the same characteristic small, white quartz grains. Fragments of grit are the commonest inclusions and vary in size from a fraction of an inch up to several feet. The smaller fragments tend to be spindle shaped and have their long axes parallel to the fine lines of the matrix. The larger fragments show less perfect orientation. In many cases the color difference between fragments and matrix is small and detection is difficult. Figure 3, sketched from an outcrop, illustrates many of these characteristics.

Microscopic examination shows that quartz and mica make up approximately 90 per cent of the matrix, the balance consisting of oligoclase, pyrrhotite, chlorite, and epidote. A chemical analysis and approximate mode are included in Table 2. Compositional banding of mica and quartz is the source of much of the foliation. Quartz occurs in several ways. Larger, rounded grains are scattered throughout a matrix of smaller, subangular grains, giving rise to a very uneven texture. Lenticular nests of quartz grains are common. It occurs embedded in mica flakes and as myrmekitic intergrowths with oligoclase. Oligoclase occurs also in small grains embedded in mica. Irregular patches enclose subangular grains of quartz. Biotite corrodes the margin of the feldspar grains in some examples. Quartz and feldspar contain abundant inclusions of sericite. Pyrrhotite occurs along cleavage planes in biotite and also as larger grains which contain small biotite foils. These large grains may be pseudomorphs.

Contacts between the Ramsay Lake grit and vein breccia are usually sharp, even in thin section. The grit immediately adjacent to the breccia matrix is commonly richer in mica than the normal

grit. With increasing distance from the matrix the amount of mica decreases, the ratio of sericite to biotite increases, and the flakes become finer grained. These changes are gradational and are observed only in thin section.

Fragments of grit or quartzite in the matrix show very little variation from their normal composition. There is a perceptible increase in mica, and pyrrhotite along cleavage planes of biotite has been noted.

VEIN BRECCIA IN THE MISSISSAGI FORMATION

The Mississagi formation consists of thick beds of arkosic quartzite and thin-bedded argillite. The conglomerate horizons described by W. H. Collins[8] have not been found at Sudbury. The principal argillite beds occur in the basal part of the formation and in places are more than 100 feet thick. They bear a superficial resemblance to the McKim graywacke. The predominant quartzite is medium grained, white to pink, and is abundantly cross-bedded. The whole formation may have a thickness of 8,000 feet. Microscopically the quartzite consists of an even-grained assemblage of quartz, plagioclase (oligoclase to andesine), biotite, and sericite. The sericite tends to be abundant in brecciated areas and less so in unbrecciated zones. Zircon is a persistent accessory mineral. A chemical analysis and approximate mode of the Mississagi matrix is included in Table 2. Mica makes up 35–40 per cent of the rock, with sericite slightly in excess. Quartz and mica together make up 75–80 per cent of the total mineral composition.

Under the microscope quartz is seen to occur as lenticular aggregates, as inclusions in mica, and as intergrowths with feldspar. Feldspar varies in amount up to 25 per cent of the matrix, and albite, oligoclase, and andesine have been identified. The albite and oligoclase occur in irregular patches and contain inclusions of quartz, andesine, and sericite. Biotite is common. Pyrrhotite, bordered by chlorite, occurs along cleavage planes in biotite. Small amounts of epidote and clinozoisite are found. Zircon occurs mostly in biotite and shows pleochroic halos. The degree of rounding, color, and zoning of the grains bears a close resemblance to the zircon of the Mississagi quartzite.

[8] "The North Shore of Lake Huron," *Can. Geol. Surv. Mem. 143* (1925).

Fragments vary in size from fractions of an inch up to several feet in stockwork breccias. Quartzite and, less commonly, argillite are the predominant types. The contacts of matrix with fragments are sharp. In thin section the quartzite fragments are seen to be slightly richer in mica at the matrix contact than elsewhere. No contacts of argillite fragments with matrix were examined.

VEIN BRECCIA IN SUDBURY GABBRO

The Sudbury gabbro occurs as sill-like bodies intruded into the Sudbury-Bruce series. It trends parallel to the strike of the sediments and varies in outcrop width from a few hundred feet to more than a mile. The rock is medium to coarse grained and gray to green in color, depending on the amount of alteration. A chemical analysis and approximate mode are included in Table 2. Since the plagioclase (labradorite to bytownite) amounts to less than 50 per cent, the rock is a melagabbro in Johannsen's classification. Hornblende is apparently secondary after pyroxene. Biotite replaces hornblende to some extent and forms intergrowths. Chlorite replaces biotite locally. In places sulphides and magnetite occupy interstices, but more commonly they lie along cleavage planes in biotite or hornblende. Quartz is not abundant and is interstitial or occurs as intergrowths with hornblende and plagioclase.

Vein breccia in gabbro near Sudbury may be seen in a small, flat outcrop near a section house a few feet north of the railway (lot 4, concession 3, McKim Township). Figure 4 is a sketch from a second locality (lot 9, concession 1, Falconbridge Township). The matrix-fragment relations are similar to those described for the Ramsay Lake and Mississagi formations. Fragments are mostly gabbro and range from a fraction of an inch up to 2 feet in diameter. A moderate degree of rounding is common. The matrix may be described as a very fine-grained green schist which under the microscope is seen to consist chiefly of a felted aggregate of small actinolite fibers and sericite flakes. Antigorite is common in some sections. Chlorite occurs as an alteration product of actinolite. Remnants of hornblende show all stages of alteration to actinolite or antigorite. The plagioclase is almost pure albite. Quartz, epidote, and clinozoisite occur sparingly as inclusions in the actinolite and mica. There is a small

amount of pyrrhotite which is usually associated with chlorite and epidote. A chemical analysis and approximate mode are included in Table 2.

Gabbro fragments in the matrix are relatively coarse grained. They contain more hornblende than the matrix, and labradorite laths are not uncommon.

CONTACT BRECCIA

Most breccia defined as "contact" is associated with gabbro. Contact breccia between McKim graywacke and gabbro contains fragments of both graywacke and gabbro. The largest fragments attain a diameter of about 2 feet. Small inclusions a fraction of an inch in diameter have a coarse, gritty appearance on weathered surfaces. The matrix is not always finer grained than the fragments, and foliation is poor in general. The coarser-textured matrix is a relatively soft, gray rock in which metacrysts of muscovite averaging about one-eighth of an inch are common. The finer-grained matrix is compact, hard, and superficially resembles massive quartzite. All these features may be seen to advantage on the north side of the outlet from Ramsay Lake (lot 6, concession 2, McKim Township). Because of the variability in the matrix and the uncertainty that it is all of the same age, it was considered inadvisable to make a chemical study for comparative purposes. An additional complication is the contact metamorphism of the graywacke by the gabbro. A field examination of unbrecciated graywacke in the vicinity of Sudbury shows common development of muscovite metacrysts near gabbro contacts. These were not seen elsewhere in the formation. As noted above, entirely similar metacrysts appear in one type of contact breccia matrix but are absent in the other. Since the field work did not lead to definite conclusions, further laboratory study has not been carried out on these graywacke-gabbro breccias.

An excellent gabbro contact breccia involving the Mississagi and Ramsay Lake formations occurs in lots 5 and 6, concession 6, Neelon Township, a few hundred feet northwest of the farmhouse at the end of the road. Figure 2 shows the field relations and the size of the larger fragments. The smaller fragments in the matrix vary from a fraction of an inch up to 10–20 inches. There is considerable folia-

tion in the matrix. Microscopic examination shows that it is composed almost entirely of biotite (50–60 per cent) and quartz (40–50 per cent), with some pyrrhotite, magnetite, epidote, and clinozoisite. No comparative chemical study of this breccia and the vein breccias has been made.

INJECTION BRECCIA

This type of breccia is less abundant than the vein and contact varieties but is perhaps the most spectacular and suggestive type of all. Several occurrences will be described.

In lot 5, concession 6, Neelon Township, an injection-breccia dike consisting mainly of fragments of Mississagi quartzite occurs on the south side of a gabbro hillside, about 600 feet from the nearest Mississagi contact. The breccia dike trends about at right angles to the regional strike, has an average width of 5 feet, and was traced for 150 feet (see Fig. 2). It contains fragments of white quartzite up to a foot in diameter cemented in a darker schistose matrix. Smaller breccia veins parallel the main injection. The gabbro at the dike contact is unaffected by the intrusion. Instead, the dike shows a 3-inch shear zone next to the gabbro in which a movement from north to south is indicated. The matrix contains quartz, plagioclase (oligoclase to andesine), biotite, clinozoisite, epidote, chlorite, and carbonate. The biotite flakes show no marked parallelism. Minute quartz veinlets traverse broken plagioclase grains but are not very continuous.

A group of similar quartzite-breccia injections in gabbro occurs near the north end of lot 12, concession 5, Dryden Township. One of these dikes is exposed for 135 feet. At the north end, where a swamp conceals it, it has a width of 14 feet. It tapers to the south and disappears in a small shear zone in the gabbro.

Another dike occurrence (in McKim Township near Sudbury golf course) was shown to the writers by H. C. Cooke. It cuts the McKim graywacke, but the fragments and matrix have their source in the Ramsay Lake formation. The matrix is moderately foliated.

COMPARISON WITH FROOD BRECCIA

The rock breccias just described show little sulphide mineralization (about 3 per cent by volume), and it is important to compare

them with ore breccias where local, high-grade mineralization has occurred. This can be done in the case of the breccia zone passing through the Frood ore body. This breccia is developed mostly in pre-Huronian basic rocks and in post-Huronian quartz diorite and has been studied in detail by the geological staff of the International Nickel Company.[9]

The field characters of the Frood breccia zone are identical with those already described here. The fragments are subangular to rounded and vary greatly in size. The largest inclusion yet mapped is south of Stobie in the south part of lot 5, concession 1, Blezard Township, and measures 2,600 feet by 900 feet. The majority of fragments are native to the host-rock with a sprinkling of foreign inclusions. The matrix contrasts in color with the fragments, weathers more easily, and is finer textured. Its mineralogical composition is as follows: 3–50 per cent hornblende (a blue-green variety with an extinction angle of 20°), 5–20 per cent biotite, 5–20 per cent quartz, 5–20 per cent oligoclase, 0–10 per cent orthoclase, 0–2 per cent titanite, 1–3 per cent metallics, 0–3 chlorite, epidote, clinozoisite, and calcite. The proportions of this mineral assemblage are too generalized for direct comparison with the breccias of the Ramsay Lake, Mississagi, and gabbro formations but could correspond in general with either the basic gabbro breccia or the highly siliceous breccia in the sediments. The most notable difference in composition is the apparent absence of sericite in the Frood breccia matrix.

Mineralization in the Frood ore body occurred through selective replacement of the matrix of brecciated quartz diorite by nickeliferous sulphides. Since no brecciated quartz diorite occurs in the rock breccia mapped by the writers, direct comparison with the ore body is not possible.

STRUCTURAL SIGNIFICANCE OF THE BRECCIA

Before presenting details of the chemical and petrofabric analysis it is desirable to show the structural position of the breccia in the complicated geologic picture at Sudbury. The geological column (Table 1) shows that the breccia is later than all the sediments and

[9] Yates, *op. cit.*, p. 169.

postdates most of the igneous rocks. It is associated in time, but not necessarily in locality, with strike faults, some of which offset the rim of the nickel basin very appreciably. These faults may be seen

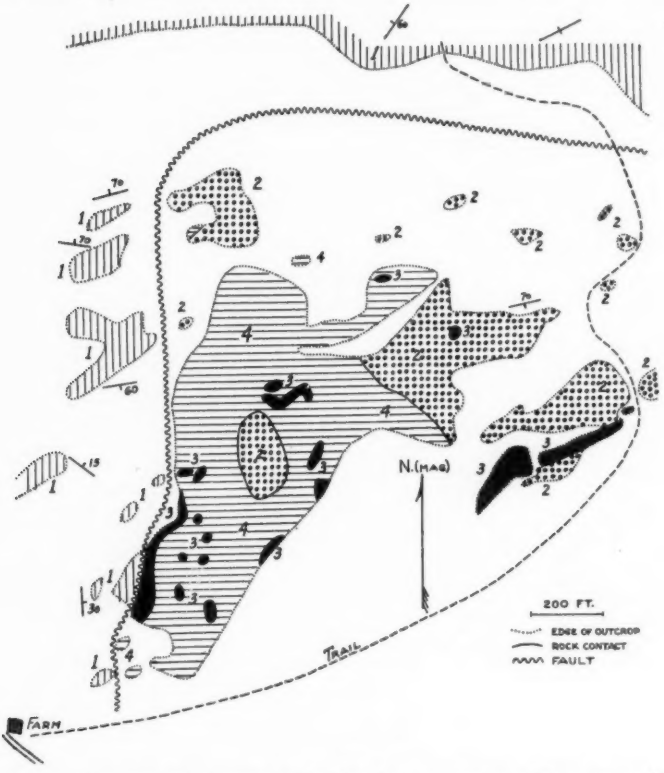

FIG. 5.—Geological relations of the breccia in lot 3, concession 4, Waters Township. *1* = Mississagi formation. *2* = Ramsay Lake conglomerate. *3* = Ramsay Lake quartzite fragments. *4* = Ramsay Lake breccia.

on the map accompanying the report by A. G. Burrows and H. C. Rickaby.[10] It is notable, however, that in few of the areas examined by the writers is there clear evidence of regional displacement along the breccia walls. Figure 5 shows one of the few cases where such

[10] "Sudbury Nickel Field Restudied," *Ont. Dept. Mines, Bull. 43*, Part 2 (1934).

faulting occurs. It is true that certain fragments indicate transportation measured in thousands of feet, but this represents displacement within the matrix and does not necessarily involve offset of the walls. The formations harboring the breccia are disturbed and shattered, and the breccia crosses formation boundaries in many places, yet in most cases these stratigraphic boundaries are essentially conformable. Pronounced shearing in narrow zones is usually absent; on the contrary a patchy, "hit-and-miss" distribution is characteristic. These features have already been described.

Despite the absence of much regional dislocation in the breccia areas the comminution of great quantities of rock to form the matrix obviously requires compressive forces. These forces are of two kinds: (1) a confining pressure (equivalent to the hydrostatic pressure exerted by fluids) and (2) a directional pressure, or stress, which is the source of the actual movement. It is thought that the confining pressure in these brecciated zones was low and that aqueous fluids of magmatic origin played a leading role in comminuting and recrystallizing the material now composing the matrix. This hypothesis is developed on a later page.

CHEMICAL AND STRUCTURAL PETROLOGY

CHEMICAL ANALYSIS OF THE BRECCIA

No previous study of the chemical relations of the breccia has been made. The suggestive mineralogical relationship between fragments and matrix already indicated makes chemical study an obvious step. An additional ground is the fine texture and foliation of the matrix which makes quantitative microscopic determination of the proportions of the minerals a difficult, if not impossible, task. As a preliminary study three pairs of chemical analyses from breccia in the Ramsay Lake, Mississagi, and gabbro formations are used to contrast matrix and fragments. With one exception all the analyses are new (see Table 2).

Attempts to calculate the proportions of each mineral in the rocks analyzed were doomed to failure, since the true composition of many of the minerals was unknown. Furthermore, the presence or absence of kaolin minerals was not determined, and the disposition of potash was thus uncertain. For each rock, therefore, an approxi-

mate mode is given which takes into account these deficiencies in the data.

The analyses may be studied by comparing equal volumes of each pair or by comparing equal weights. Both methods are instructive. If constant volume is assumed in the development of a breccia matrix from a host-rock, the actual gains and losses of each constituent can be computed. If equal weights are compared, the trend of chemical variation between matrix and fragments can be inferred.

There is no evidence in the Sudbury breccias either for or against the assumption of constant volume. The matrix problem is not analogous to the usual wallrock-alteration study where replacement can be shown in many cases to be essentially volume for volume. The breccia field relations definitely show that the matrix is not developed in place, and thus the constant-volume question is an open one. The gains and losses recorded in Tables 4, 5, and 6 are to be considered therefore as possibilities only.

With the exception of H_2O the minor constituents CO_2, TiO_2, P_2O_5, and FeS_2 are omitted from the calculation. The constant-volume method, developed by W. Lindgren,[11] is well known and need not be described in detail here. The porosities of the analyzed rocks have not been determined. However, any error arising from this source is likely to be small and, in view of the unsupported assumption of constant volume, would be an unnecessary refinement.

Gains and losses in the Ramsay Lake analyses are small, Na_2O excepted. There is a gain in SiO_2 which is not shown by inspection of the original analyses. The Mississagi and gabbro pairs show significant changes in the same direction indicated by the original analyses. H_2O is not consistent. All these absolute gains and losses may be compared with the relative gains and losses plotted in the straight-line diagram of Figure 6. Both computations show similar trends. The gain in soda for all three pairs is pronounced.

Study of the analyses by comparing equal weights is more instructive than the equal-volumes method. After consideration of several methods, P. Niggli's system[12] was finally selected and Table 7 pre-

[11] "The Nature of Replacement," *Econ. Geol.*, Vol. VII (1912), p. 521.

[12] "Zur Zusammensetzung und Bildung der Sericite," *Schw. Miner. Mitt.*, Vol. XIII (1933), p. 84.

TABLE 3

ANALYSES RECALCULATED TO 100 PER CENT

	1	2	3	4	5	6
SiO_2	77.37	77.22	83.79	69.97	50.44	56.10
Al_2O_3	11.29	11.49	9.69	14.32	12.03	14.87
Fe_2O_3	0.99	0.64	0.69	1.89	1.48	0.67
FeO	2.45	2.66	0.77	2.93	5.63	5.07
CaO	0.77	0.81	0.06	0.07	13.99	8.89
MgO	1.29	1.36	0.78	2.52	12.30	8.02
K_2O	3.15	3.08	1.24	4.08	0.51	0.22
Na_2O	0.18	0.40	1.87	2.20	0.83	3.80
H_2O	1.37	1.32	0.58	1.35	1.82	0.99
CO_2	0.15	tr	0.32	0.20	0.56	0.40
TiO_2	0.45	0.47	0.16	0.40	0.34	0.67
P_2O_5	0.07	0.06	0.05	0.07	0.07	0.09
FeS_2	0.47	0.49	tr	tr	.....	0.21
Total	100.00	100.00	100.00	100.00	100.00	100.00

TABLE 4*

GAINS AND LOSSES OF RAMSAY LAKE GRIT (RL) IN THE CHANGE TO BRECCIA MATRIX (B), ASSUMING CONSTANT VOLUME

	100 cc. RL Contains	100 cc. B Contains	Gain + Loss − in Gm.	Gain or Loss in Percentage
SiO_2	211.76	216.83	+5.07	+ 2.4
Al_2O_3	30.90	32.26	+1.36	+ 4.2
Fe_2O_3	2.71	1.80	−0.91	− 33.5
FeO	6.71	7.47	+0.76	+ 11.3
CaO	2.11	2.28	+0.17	+ 8.5
MgO	3.53	3.82	+0.29	+ 8.3
K_2O	8.62	8.65	+0.03	+ 0.3
Na_2O	0.49	1.12	+0.63	+126.0
H_2O	3.75	3.71	−0.04	− 1.0
Others	3.12	2.86	−0.26	− 8.7
Total	273.70	280.80	.....	.....

* This table and Tables 5, and 6 show the calculation of gains and losses, assuming constant volume: (Weight per cent of each constituent) × (Spec. gr. of rock) = (Weight of each constituent in 100 cc. of rock).

TABLE 5*

GAINS AND LOSSES OF MISSISSAGI QUARTZITE (M) IN THE CHANGE TO BRECCIA MATRIX (B), ASSUMING CONSTANT VOLUME

	100 cc. M Contains	100 cc. B Contains	Gain + Loss − in Gm.	Gain or Loss in Percentage
SiO_2	223.55	192.77	−30.78	− 13.8
Al_2O_3	25.94	39.45	+13.51	+ 52.0
Fe_2O_3	1.84	5.21	+ 3.37	+183.1
FeO	2.06	8.07	+ 6.01	+291.7
CaO	0.16	0.19	+ 0.03	+ 18.8
MgO	2.08	6.94	+ 4.86	+233.6
K_2O	3.29	11.24	+ 7.95	+241.7
Na_2O	4.99	6.06	+ 1.07	+ 21.6
H_2O	1.55	3.72	+ 2.17	+140.0
Others	1.36	1.90	+ 0.54	+ 40.0
Total	266.82	275.55		

* See note to Table 4.

TABLE 6*

GAINS AND LOSSES OF SUDBURY GABBRO (G) IN THE CHANGE TO BRECCIA MATRIX (B), ASSUMING CONSTANT VOLUME

	100 cc. G Contains	100 cc. B Contains	Gain + Loss − in Gm.	Gain or Loss in Percentage
SiO_2	151.32	161.34	+10.02	+ 6.6
Al_2O_3	36.09	42.77	+ 6.68	+ 18.6
Fe_2O_3	4.44	1.93	− 2.51	− 62.7
FeO	16.89	14.58	− 2.31	− 13.6
CaO	41.97	25.57	−16.40	− 40.0
MgO	36.90	23.07	−13.83	− 37.4
K_2O	1.53	0.63	− 0.90	− 58.8
Na_2O	2.49	10.93	+ 8.44	+337.6
H_2O	5.46	2.85	− 2.61	− 47.8
Others	2.91	3.94	+ 1.03	+ 32.1
Total	300.00	287.61		

* See note to Table 4.

pared as follows. The eight chief constituents of Table 2 have been recalculated to 100 per cent with deletion of the second decimal place. Each weight percentage is converted to molecular proportions and multiplied by 1,000 to remove decimals. The number determined for F_2O_3 is multiplied by 2 and added to that obtained for

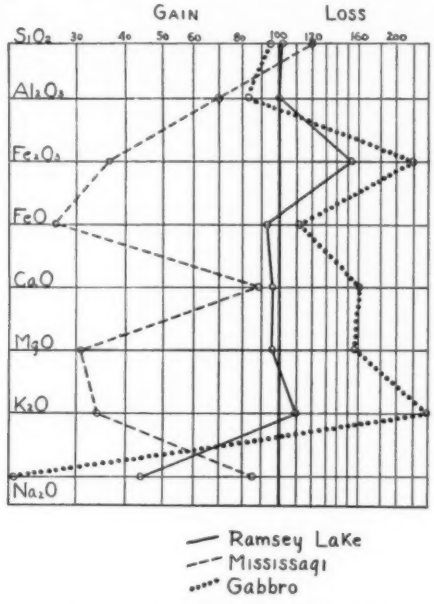

FIG. 6.—Relative gains and losses of the chief constituents shown on a straight-line diagram. Constant volume not assumed.

FeO.[13] This new number is added to the MgO number and given the symbol *fm*. The alkali numbers are added together and are represented by the symbol *alk*. The remaining symbols in Table 6 need no explanation. Comparison of analyses can now be made on the basis of five instead of eight constituents.

Figure 7 is a diagram constructed with these values, in which the horizontal co-ordinate represents molecular proportions of silica; the

[13] This is permissible because (mol. prop. of *n* per cent Fe_2O_3) × 2 = (mol. prop. of *n* per cent FeO) approximately.

vertical co-ordinate, the molecular proportions of the other constituents. The silica contents shown in analyses 1–6, Table 7, are plotted on the horizontal co-ordinate, and from each point a vertical is erected on which the corresponding *al*, *fm*, *c*, and *alk* values are plotted. Lines are then drawn connecting the corresponding points

TABLE 7

SIMPLIFIED WEIGHT PERCENTAGE OF CONSTITUENTS AND THE MOLECULAR PROPORTIONS DERIVED FROM THEM USING NIGGLI'S SYSTEM

	1	2	3	4	5	6	7
SiO_2	79.6	79.0	84.8	71.4	52.2	57.5	62.11
Al_2O_3	11.6	11.8	9.8	14.6	12.4	15.2	17.78
Fe_2O_3	1.0	0.7	0.7	1.9	1.5	0.7	Total Fe 6.32
FeO	2.5	2.7	0.8	3.0	5.8	5.2	.....
CaO	0.8	0.8	0.1	0.1	14.5	9.0	1.69
MgO	1.3	1.4	0.8	2.6	12.7	8.2	4.52
K_2O	3.2	3.1	1.2	4.2	0.5	0.2	0.94
Na_2O	0.2	0.4	1.9	2.2	0.8	3.9	5.95
	Molecular Proportions × 1,000						
si	1326	1316	1413	1190	870	958	1035
al	118	116	96	143	121	149	174
fm	79	81	39	131	414	283	200
c	14	14	2	2	259	161	30
alk	37	39	44	81	18	65	106

si = SiO_2; *al* = Al_2O_3; *fm* = Fe_2O_3 + FeO + MgO; *c* = CaO; *alk* = Na_2O + K_2O.

1. Ramsay Lake grit.
2. Ramsay Lake breccia matrix.
3. Mississagi quartzite.
4. Mississagi breccia matrix.
5. Sudbury gabbro.
6. Gabbro breccia matrix.
7. Hypothetical "rock" obtained from Fig. 8.

for each of the three pairs of analyses; thus, a line is drawn from the *al* value on analysis 1 to that on 2, from 3 to 4, from 5 to 6. If these lines are projected, it is found that the three *al* lines meet at a point, as do also the three *alk* lines; and, further, that the two points thus obtained fall on a vertical line representing 1,035 molecular proportions of silica. The three *fm* lines do not intersect at a common point, but they do intersect by pairs on approximately the same vertical line. The *c* lines have no common intersection, and only one of the

pair intersections is close to the above vertical; but, as CaO values in the analyses are small, experimental error in the original determinations could have important effects on the course of these lines.

It would seem, therefore, that the trend of the change from rock to breccia is, in each case, toward a "rock" of definite composition, al-

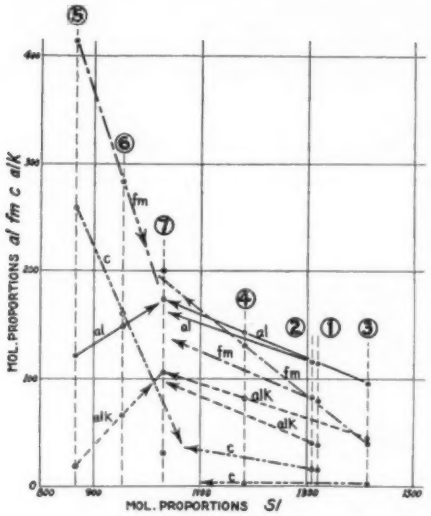

FIG. 7.—Silica variation diagram in terms of *al*, *fm*, *c*, and *alk*. *1* = Ramsay Lake grit. *2* = Ramsay Lake breccia matrix. *3* = Mississagi quartzite. *4* = Mississagi breccia matrix. *5* = Sudbury gabbro. *6* = Gabbro breccia matrix. *7* = Hypothetical "rock." The slopes of *al*, *c*, *fm*, and *alk* for the Ramsay Lake pair of analyses were first determined on an enlarged scale drawing in order to extrapolate more accurately toward the hypothetical "rock."

though in no case is that composition attained. The molecular composition of this hypothetical rock, as read from the diagram, is shown in Table 7, Column 7. Its approximate percentage composition is also given.[14]

[14] Values for Na_2O and K_2O were obtained: (1) by plotting them individually for the three pairs of analyses (not shown in Fig. 7) and (2) by dividing the *alk* value for the hypothetical rock proportionately between them. A similar method was used to determine individual values for MgO and FeO.

These relations are shown on a triangular diagram in Figure 8, using weight percentages of the constituents but retaining Niggli's grouping. The hypothetical rock obtained from the silica-variation diagram occupies here also an intermediate position.

DISCUSSION OF CHEMICAL ANALYSIS

Field and microscopic examination of the breccia indicate clearly an enrichment in mica in the matrix. Microscopic study shows also the presence in the matrix of plagioclase more sodic than that in the

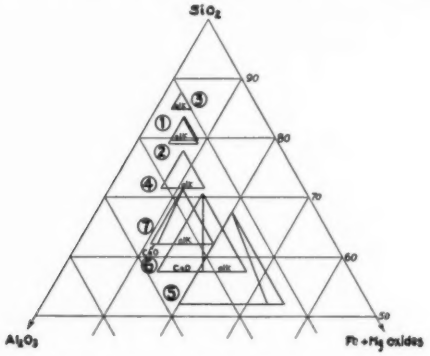

FIG. 8.—Triangular diagram showing the chemical variation of the analyses in terms of the principal constituents. The numbers refer to the same rocks as in Fig. 8.

fragments. Other changes are less consistent than these two. There is a discrepancy, however, between the plagioclase calculated from the chemical analyses and that found in the rock. The latter is less sodic than the calculated plagioclase. This means that there is probably more sodium in the mica than the usual muscovite formula allows for. Niggli[15] has already reported sericite which is higher in alkalis and silica than muscovite. In any subsequent investigation of the breccia it would be desirable to isolate and analyze sericite chemically and identify beyond doubt the source of the excess sodium.

The chemical analysis of the breccia shows clearly that recrystallization and neocrystallization, without change in bulk chemical

[15] *Op. cit.*, p. 84.

composition, are inadequate to explain the source of the matrixes. The hypothetical rock in Figure 7 and Table 7 has the only proportions of constituents which would have been unaffected chemically by the solutions available at the time of brecciation. All other compositions (in this case represented by the gabbro, quartzite, and grit) are altered to matrixes whose compositions converge toward this hypothetical composition. Inspection of its constituents indicates proportions common to igneous rather than sedimentary rocks. Compared with an "average" igneous rock, this hypothetical composition is higher in Al_2O_3, MgO, and Na_2O and lower in CaO and K_2O. It is in general of an alkaline composition, except that normal alkaline rocks are usually rich in K_2O if MgO is high, and rich in FeO and Fe_2O_3 if Na_2O is high.

The proportions of water in the analyses seem inconsistent at first sight with the role ascribed to it in forming the breccia matrix. There is less H_2O in the Ramsay Lake and gabbro breccia matrixes than in the corresponding grit and gabbro. The Mississagi alone shows more H_2O in the matrix than in the quartzite. There is nothing inconsistent in these relations, if it is remembered that the H_2O in these (or any other) rocks merely represents the water combined with the rock minerals and that the amount and kind of these minerals is a function of temperature and concentration only. The amount of H_2O in a chemical analysis is not a criterion of the amount of H_2O which may have been active during the formational period of the rock. The generally accepted thesis that hydrothermal activity is brought about by dilute aqueous fluids carrying small quantities of other materials lends emphasis to the question. In the breccia matrixes, for example, soda is consistently higher than in the corresponding fragments. The amount of water necessary to bring about this increase certainly does not show in the chemical analysis, and the excess not needed to develop OH minerals stable at the given temperature level is therefore expelled into the interstices and is free to escape.

PETROFABRIC ANALYSIS

Fully as necessary as chemical analysis of the breccia is a petrofabric analysis to establish the mineral orientation in the matrix. These data, correlated with the field observations, will then give the

best possible working hypothesis to explain the development of the breccia.

The petrofabric analysis, like the preceding chemical analysis, represents only a preliminary survey of the problem, and the entire area mapped in the field has not been sampled adequately by any means. The results obtained fall below expectations, and the present interpretation may be erroneous.

Quartz is the principal mineral whose orientation was established. A few measurements of mica cleavages were also made, but these were less necessary because of the visible parallel arrangement of most of the mica foils. The thin sections examined are all perpendicular to the foliation (or bedding) of the rocks and, if lineation is visible, perpendicular to that also. The letter *b* denotes lineation in all cases. The orientation of the quartz-crystal axes is determined with a universal stage attachment, and the horizontal and vertical angles are plotted on an equal-area projection. A system of contouring is used to delimit the relative degree of concentration from place to place on the projection. This technique is adequately described elsewhere.[16]

A very common quartz orientation in deformed rocks such as schists, quartzites, etc., is an arrangement whereby the chief concentrations of axes are spread ringlike about the lineation *b*, usually at angles 60°–90° from *b*. This is commonly described as a girdle orientation. A minimum concentration occurs at *b*. This is one of the really important "fingerprints" of rock deformation, and, although its interpretation is still obscure,[17] it can be used in a comparative way with success.

A number of quartz diagrams of breccia matrix and of unbrecciated rock were prepared. There is very little orientation in either type, but the unbrecciated material shows somewhat more indication of a girdle than the matrix. Figure 9 of a matrix specimen indicates random orientation, even though the associated mica gives a distinct foliation *s* and lineation *b*. However, until further petro-

[16] E. B. Knopf and Earl Ingerson, "Structural Petrology," *Geol. Soc. Amer. Mem. 6* (1938).

[17] Fairbairn, "Hypotheses of Quartz Orientation, etc.," *Bull. Geol. Soc. Amer.*, Vol. L (1939), p. 1475.

fabric work is carried out, it would be pointless to publish and attempt a detailed comparison of the remaining diagrams.

The poor crystallographic orientation of the quartz in the matrix may be interpreted as the result of predominant intergranular, rather than intragranular, movement. Low confining pressure at the time of matrix development could be responsible for this condition. High confining pressure would tend to inhibit intergranular movement and favor intragranular movement. Indirect support for this

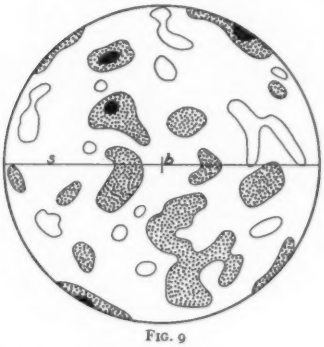

FIG. 9

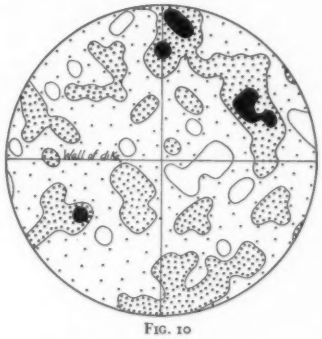

FIG. 10

FIG. 9.—Diagram showing 385 quartz axes from the Ramsay Lake breccia matrix. S = foliation of the matrix. 3–2–1–0 per cent contours.

FIG. 10.—Diagram showing 418 quartz axes from a sandstone dike. 3–2–1–0 per cent contours.

assumption may be derived from the orientation of quartz in a sandstone "dike" found in the breccia area. These dikes have been described by W. H. Collins[18] and have no connection with the breccia. The quartz orientation in a small dike of this type at the east end of Kelley Lake (boundary of lots 9 and 10, concession 1, McKim Township) is shown in Figure 10. Its orientation may be described as random, as might be expected, since the grains lie in a small fracture which was filled with unconsolidated material from an overlying sand. Intergranular movement predominated, and subsequent deformation was not pronounced enough to disturb the initial random orientation.

[18] "The North Shore of Lake Huron," *Can. Geol. Surv. Mem. 143* (1925).

It is not intended to suggest from this analogy that the breccia matrix originated in the same way as the sandstone dike. It is desired only to emphasize a probable deficiency of confining pressure adequate to produce much intragranular movement. This is not incompatible with the conspicuous dimensional orientation of mica in the matrix. A parallel arrangement of tabular crystals such as mica may originate in a number of ways, and, in view of the favored origin for the matrix to be described, no discrepancy in quartz-mica relations is indicated.

SUMMARY OF DATA

Before considering the origin of the breccia a résumé of the more pertinent data is desirable.

1. Although related chronologically, the breccia is not necessarily related spatially to the post-norite faults of the region. Formations enclosing it are not offset as a rule. The breccia lies in more or less definite zones, but in detail its distribution is irregular, and it does not lie in "shear zones" of the type usually associated with faulting.

2. The fragments are subangular to rounded. Although commonly local in origin, transportation for thousands of feet is necessary to account for many others.

3. Sinuous layers of mica flakes oriented parallel to walls and fragments are typical. The mica occurs also in swirls and small folds, and there is commonly a compositional banding of alternate mica-rich and mica-poor layers.

4. Small breccia veins appear in many cases to be isolated from larger feeders, yet possess the ability to penetrate into small crevices.

5. On the basis of two calculations made on presumably average outcrops, the volume of fragments is somewhat greater than the volume of the matrix. There is no evidence of chilling at the contacts. The matrix shows little textural uniformity, although it is distinctly finer grained than the host rock.

6. Hydroxyl (OH-bearing) minerals, chlorite, sericite, epidote-clinozoisite, etc., are usually more abundant in the matrix than in fragments. Pyrrhotite in small quantities is characteristic.

7. The margins of fragments are in places richer in hydroxyl minerals than the centers. Vermicular quartz is common in the matrix.

The matrix of the Mississagi breccia contains zircons which are similar to those in the unbrecciated rock.

8. There is a marked gain in soda for the three rock types studied. Sodic plagioclase does not account for all of it.

9. A silica-variation diagram of the chemical analyses taken in pairs (fragment-matrix) for each breccia type shows convergence toward a common hypothetical "rock." This rock has igneous characters and may be considered to have that composition which represents equilibrium under the conditions existing when the breccia was formed.

10. Petrofabric analysis of quartz in the breccia indicates the predominance of intergranular over intragranular movement. This suggests low confining pressure.

ORIGIN OF THE BRECCIA

Breccias may originate in a number of ways, and discrimination is naturally dependent on the character of each. The possibility of volcanic origin of the Sudbury breccia will be considered first. This hypothesis implies a matrix which was in large part molten at the time of injection. There are several weighty reasons against this view.

1. The age of the breccia is definitely fixed in the time scale. As no unbrecciated rocks of volcanic origin and of that age are known at Sudbury, doubt is cast immediately on the volcanic origin of a breccia as widespread as this one is known to be. Furthermore, only one volcanic fragment has been found in the matrix. This would be unusual in a true volcanic breccia.

2. With the exception of the relatively uncommon breccia in the gabbro the matrixes are too rich in quartz to have been molten during their formation unless unusual temperatures are assumed. No normal igneous crystallization produces quartz in the proportions found in the Ramsay Lake and Mississagi matrixes; only in pegmatite dikes and quartz veins can such proportions develop. The breccia minerals—sericite, biotite, plagioclase, epidote, etc.—do not indicate unusual temperatures, and their proportions and texture prevent classification of the rock as "pegmatite" or "quartz vein." There is no textural evidence of silicification which would account

for the high quartz content by later replacement of an igneous matrix.

3. Finally, the close chemical and mineralogical relation between matrix and host-rock or fragments (most of them sediments) makes a volcanic origin quite untenable.

Exclusion of direct igneous origin for the breccia leads next to consideration of a matrix whose particles were essentially solid at all stages. Replacement breccia and structural breccia are two types which fall under this head. The former is a pseudo-breccia formed by high-grade, hydrothermal metamorphism in which the "matrix" increases in volume at the expense of the "fragments" solely by replacement. Deformation plays no part in the process. A few reasons against a replacement origin at Sudbury are: (1) deformation and movement play an important part in forming the breccia; (2) feldspathization and development of porphyroblasts, essential to the replacement breccia (or to any other rock formed under high-grade metamorphism), are not known in the Sudbury breccia; and (3) gradational contacts between fragments and matrix, commonly found in replacement breccias, are absent here.

There remains for consideration only the structural breccia. The facts derived from the present investigation support without exception the hypothesis of a breccia formed by a combination of movement and hydrothermal activity. Its history may therefore have been as follows: In post-Huronian time, after the intrusion of the gabbro, norite, and later granites, the Sudbury region underwent deformation. This deformation folded the Whitewater series, faulted the southwest rim of the norite basin, and was responsible for extensive brecciation along the entire south side, principally in the gabbro and Bruce series. Dikes crosscutting all the deformed rocks fill fissures formed by tensional forces which accompanied the orogeny. This constitutes in brief the orogenic background of the breccia.

The brecciation was accompanied from the very start by fluids of magmatic origin, possibly gases, under high pressure. Water was the principal component, and there was enough sodium to account for the gain noted in all the matrixes. Highly irregular but approximately strikewise fractures were opened. In places along these fractures tensional forces predominated; elsewhere there was compression.

Low confining rock pressure prevailed. Fragments large and small were torn loose from the walls and gradually comminuted by joint action of the steam and movement. In time a mobile matrix formed which attained sufficient volume to transport the remaining solid fragments. The calculated matrix volumes of 36 per cent and 45 per cent are probably higher than the minimum volume necessary to initiate this transport. This breccia "mud," saturated with water and under high temperature and pressure, was able to penetrate small crevices for scores of feet. A permanent record of its flow is preserved in the dimensional orientation of mica flakes which it carried along. These follow faithfully the boundaries of fragments or form swirls and small folds in the matrix. This flow developed compositional banding, and in many places the matrix shows alternate mica-rich and mica-poor layers. The equant quartz grains show no dimensional orientation, and, since their movements were controlled by the all-pervading fluid (movement intergranular only), they show no crystallographic orientation. The combination of low confining pressure and moderate stress would also be unfavorable to crystallographic orientation of quartz.

Chemically, a number of changes occurred in the breccia mud, chief of which was enrichment in sodium. Mineralogically, there was an increase in sericite, chlorite, epidote, sodic plagioclase, etc. Matrixes derived from different host-rocks tend to converge toward a hypothetical "rock" whose composition represents equilibrium under the existing pressure, temperature, and concentration.

The mobile matrix continued its activity for a period sufficiently long to transport large fragments for hundreds (in some cases thousands) of feet. This transportation was upward in general but was not accompanied as a rule by extensive offsetting of the breccia walls. Only in the initial stages of the brecciation, when extensive comminution took place, was dislocation necessary. Later, when the mobile matrix had attained sufficient volume relative to the fragments, further dislocation was unnecessary and played no part in the transportation of fragments. Indeed, it is not impossible that the dislocated walls under certain conditions might slip back toward their original positions under the lubricating action of the fluid-saturated matrix.

The final phase was the cooling and consolidation of the breccia matrix into a recrystallized, foliated rock in which the originally suspended fragments are now frozen. Then came sulphide mineralization which produced ore breccia in certain localities but for the most part resulted in minor changes only. In the matrix of the rock breccia nickeliferous pyrrhotite partially replaced biotite along cleavage planes and was then surrounded by a corona of chlorite. In more recent time the slight weathering of exposed surfaces has etched out the matrix-fragment boundaries and accentuated many of the details which record the flow of the once mobile matrix.

The kernel of the above hypothesis is contained in Fraser's report[19] on the neighboring Frood breccia. He attributes its origin to the action of a gas or highly attenuated solution. He considers that this would explain: (1) the penetrative power of the breccia, (2) its localization without evidence of channelways, and (3) the recrystallization of the matrix without marked change in composition.

OTHER BRECCIAS OF THE SUDBURY TYPE

There is little information available on breccia of the Sudbury type. Many structural breccias are known in ore-bearing districts but are inadequately described. Fraser[20] states that he has seen breccias in the western United States identical with the Frood breccia which he studied. In the Tintic district of Utah, R. Farmin[21] has recently described a "pebble dike" breccia which has many features in common with the Sudbury breccia. Rounded fragments from $\frac{1}{10}$ inch to 15 inches in diameter occur in matrixes consisting of either fine-grained porphyry, jasperoid, or carbonate. The fragments originate mostly in the horizon immediately adjacent to the breccia, but not a few have been found which must have been transported more than 6,000 feet. Although his field observations are unsupported by detailed laboratory work, Farmin's conclusion concerning the origin of these pebble dikes is fundamentally the same as that advanced for the Sudbury breccia. The fragments were broken from underlying

[19] *Op. cit.* [20] Personal communication.

[21] " 'Pebble Dikes' and Associated Mineralization at Tintic, Utah," *Econ. Geol.*, Vol. XXIX (1934), p. 356.

formations with the aid of magmatic fluids and were injected upward into the country rock.

It is probable that other breccias of the Sudbury and Tintic types occur in various parts of the world. Their study is to be recommended for two reasons: (1) they may have economic significance in ore districts, and (2) they throw light on fundamental chemical and structural problems.

CONCLUSION

The preceding description and interpretation of the Sudbury rock breccias combines field, chemical, and petrofabric methods in an attempt to give a rational picture of the brecciation process. The field work needs to be extended to include more of the breccia, and additional chemical and petrofabric analyses would be highly desirable. The authors believe that present results point the way for further work but do not hold their conclusions to be final. Problems connected with the rock breccia will always be important at Sudbury because of their relation to the ore breccia. Information gained from study of one is likely to be useful in interpreting the other. Therefore the circumstance that the present study has no immediate economic importance should not act as a deterrent to future work.

ACKNOWLEDGMENTS.—During the course of the field work and in preparation of the manuscript the authors had the advantage of association with H. C. Cooke, of the Geological Survey at Ottawa. Dr. Cooke's field experience at Sudbury was of considerable aid, and his active interest in the breccia problem is greatly appreciated. A. B. Yates and others connected with the International Nickel Company geological staff were also helpful in many ways. Able assistance in mapping was given by J. Talbot, D. A. Firth, and J. S. Poupore. Finally, the authors acknowledge their indebtedness to the Ontario Department of Mines, which sponsored the project as part of a program of field work in the vicinity of Sudbury.

LOWER AND MIDDLE MISSISSIPPIAN STRATIGRAPHY OF OHIO

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ABSTRACT

The Lower and Middle Mississippian rocks of Ohio are briefly described. The principal stratigraphic problem is the subdivision of the Cuyahoga and Logan formations into facies and members. For these two formations some new member and facies names are proposed, and a possible explanation for the conditions of their deposition is suggested.

INTRODUCTION

The Lower and Middle Mississippian strata of Ohio consist of five formations, which are, in ascending order, the Bedford shale, the Berea sandstone, the Sunbury shale, the Cuyahoga formation, and the Logan formation. Most attention has been given to the problem of subdividing the Cuyahoga and Logan formations into a number of members and lithologic facies. Correlations between the various members of these two formations have been made partly by faunal evidence but more largely on the bases of stratigraphic position and succession. In this report some of the older classifications of the Cuyahoga and Logan formations have been modified and several new stratigraphic subdivisions have been proposed.

For the purpose of showing the areal distribution and regional structure of the Lower and Middle Mississippian formations in Ohio, a geological map with horizontal and vertical sections has been constructed. A table to indicate the general relationships of the various formations and their subdivisions is presented, together with index maps showing the geographic locations of the facies composing the Cuyahoga and Logan formations.

BEDFORD FORMATION

Resting on the Ohio shale of late Devonian age is the Bedford formation, named by Newberry from the excellent outcrops in the gorge of Tinkers Creek at Bedford, Cuyahoga County, Ohio. The Bedford consists essentially of argillaceous shales with a few

thin nonpersistent layers of sandstone. The outcrop area of the Bedford occupies a narrow zone in northern Ohio westward from the Ohio-Pennsylvania border to north-central Ohio and thence southward through the center of the state to the Ohio River.

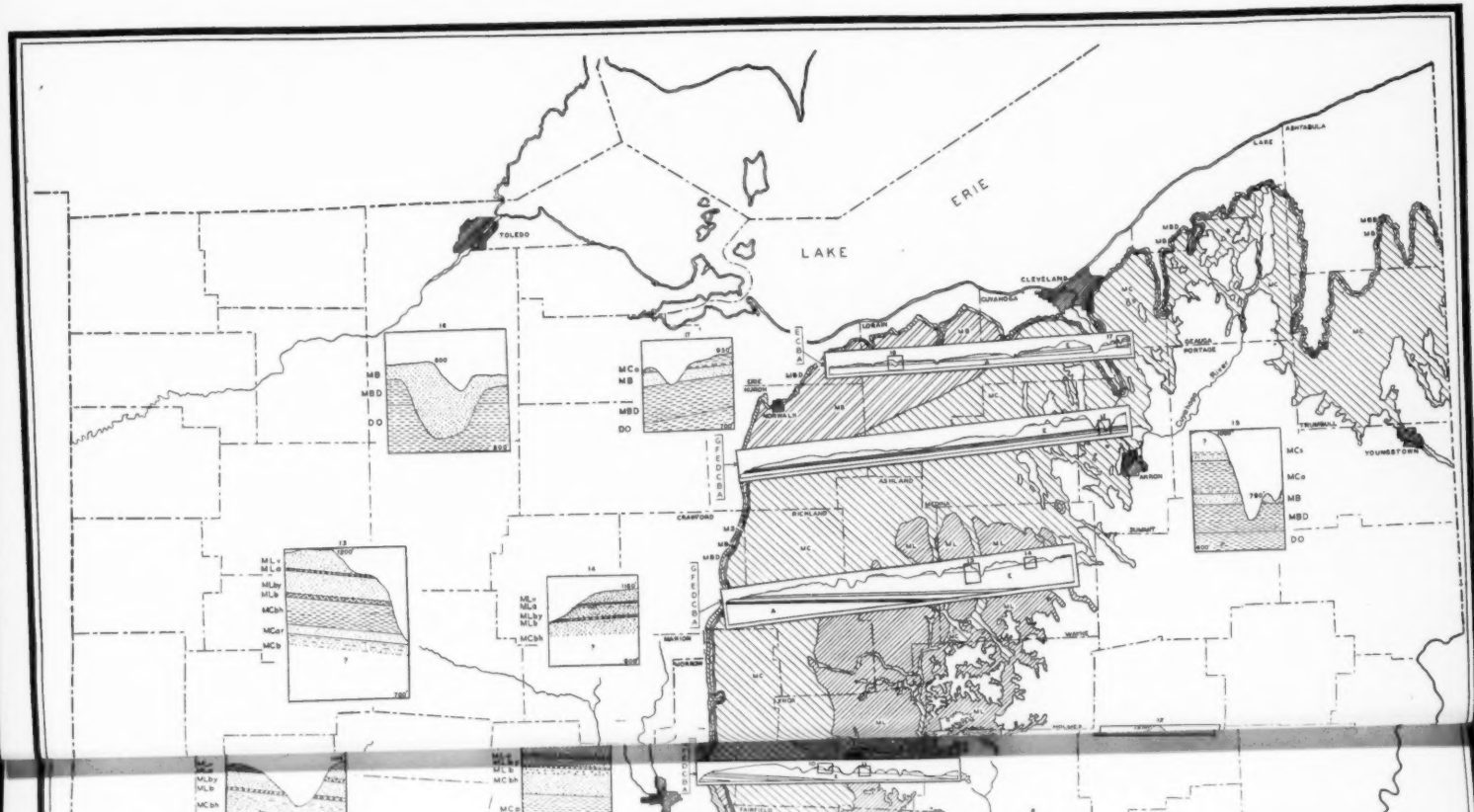
TABLE 1

GENERAL SECTION ON TINKERS CREEK AT BEDFORD, CUYAHOGA COUNTY

	Feet	Inches
CUYAHOGA FORMATION		
Orangeville member:		
Blue and blue-black shale with some black streaks	12	
Aurora submember:		
Blue-gray and gray, fine-grained sandstone layers alternating with blue-gray shale layers	8	3
Blue-gray, thinly laminated, argillaceous shale, tending to split into very small fragments	5	8
Black, very thinly laminated, fossiliferous shale	..	1
BEREA FORMATION (altitude at base approximately 875 feet A.T.)		
Massive, gray to gray-buff, medium- and coarse-grained sandstone	22	
Thin, blue-gray, medium-grained sandstone with ripple marks	6	
Gray, medium-grained, massive sandstone	10	
BEDFORD FORMATION		
Blue-gray, sandy shales alternating with thin, fine-grained sandstones and siltstones	25	
Blue-gray, fine-grained sandstone and siltstone	22	
Blue-gray, argillaceous to arenaceous shales with thin lenses of siltstone	40	
OHIO SHALE (DEVONIAN)		

The Bedford shales throughout northern Ohio vary in color from one locality to another. In eastern Cuyahoga County the prevailing color is blue with some dark red or maroon, but farther west there is a general increase in the amount of red, although some sections have no red shale. Wherever exposed, the basal few feet of the Bedford are generally black, fissile, argillaceous shales.

The light blue-gray sandstone layers are composed of fine-grained sand and silt. Commonly from 3 to 12 inches thick, they are interbedded singly with shales. Most of the sandstone layers are ripple


LAKE
ERIE
TOLEDO
CLEVELAND
CUYAHOGA
LORAIN
ERIE
HURON
RICHLAND
ASHLAND
WAYNE
PORTAGE
SUMMIT
MEDINA
ASHTABULA
TRUMBULL
YOUNGSTOWN
AKRON
CRAWFORD
MARION
FAIRFIELD
MUSKINGUM
MORROW
KNOX
LICKING
DELAWARE
FRANKLIN
PICKAWAY
ROSS
HOCKING
VINTON
JACKSON
MEIGS
GALLIA
LAWRENCE
SCIOTO
PIKE
ADAMS
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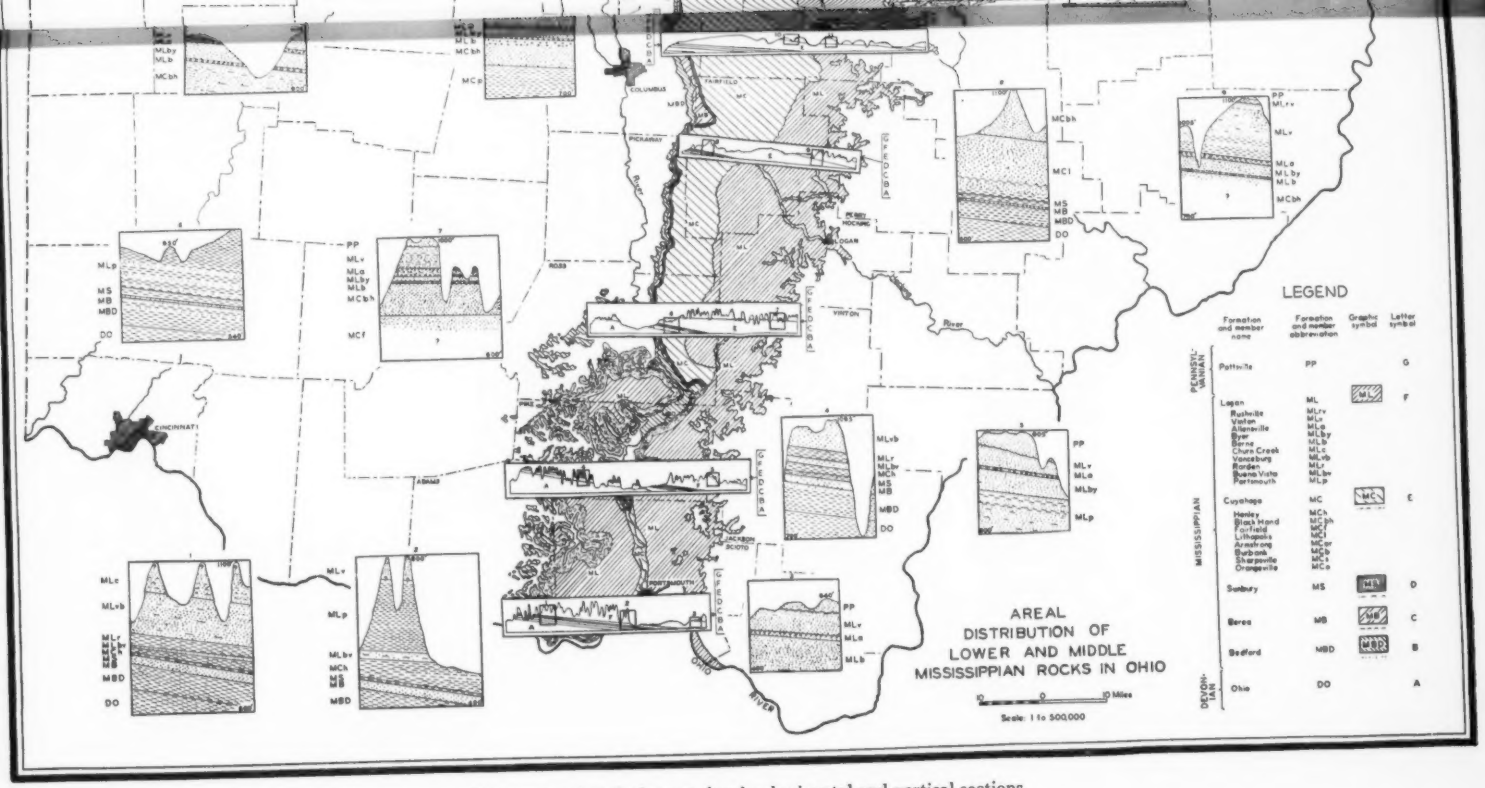


FIG. 1.—Areal geologic map showing horizontal and vertical sections

marked. Locally they may thicken very considerably, as in the case of the Euclid lentil,[1] which is 20 feet thick in the vicinity of Cleveland, though areally of small extent.

From western Cuyahoga County west for some 40 miles into north-central Ohio the basal 5–15 feet of the Bedford are either black fissile shales or red argillaceous shales interbedded with thin, buff to gray, fine-grained sandstone, and overlain by 25–30 feet of blue, gray, or chocolate sandy shales containing a few thin layers of gray sandstones and gray limestones. This sequence is succeeded by 40–50 feet of chocolate and lavender argillaceous shales. No good exposures of the Bedford occur along the western outcrop zone of the Mississippian rocks in north-central Ohio, owing to the low relief and the cover of glacial drift.

The best exposures of the Bedford in central Ohio occur near Gahanna, Franklin County, where the formation consists of blue-gray, chocolate, and red shales through a vertical thickness of 90 feet.

In south-central Ohio the thickness of the Bedford varies from 80 to 110 feet. Generally in this region it displays at the base 10–20 feet of thin sandstones, sometimes interbedded with thin shale layers, overlain by 70–90 feet of chocolate, tan, and dark-gray shales (see the section in Table 8).

In many places in northern Ohio the basal portions of the Bedford have been structurally disturbed. Small folds are not uncommon, and locally they are complicated by thrust faults. No great thickness of the formation is involved, and neither underlying nor overlying beds are affected, indicating that the disturbance took place at or shortly after deposition of the materials.

Only a slight disconformity, marked largely by a sharp contact of contrasting shales, is present between the Bedford and the underlying Ohio shale. Fossils are found only in the basal 3–30 inches of the Bedford, where they are rather common.

BEREA FORMATION

Newberry gave the name "Berea sandstone" for outcrops at Berea, Cuyahoga County. The formation, occupying a narrow

[1] C. S. Prosser, "The Devonian and Mississippian Formations of Northeastern Ohio," *Ohio Geol. Surv.*, Bull. 15 (4th ser., 1912), p. 51.

outcrop zone, lies disconformably above the Bedford and is in turn overlain by the Sunbury shale from the Ohio River in south-central Ohio to Huron County in north-central Ohio and by the Cuyahoga formation from Huron County eastward to the Pennsylvania state line.

The Berea is a tan, light-gray or white, quartz sandstone, locally having a brown iron stain on weathered surfaces. Along the northern outcrop area in Ohio it is a fine-grained sandstone, but from Erie County southward there is a progressive decrease in grain size,[2] so that within 150 miles, at Waverly, it is a siltstone.

The thickness of the Berea varies considerably, especially in northern Ohio, where it was deposited on a surface of considerable relief. Where deep erosional channels were filled it exceeds 200 feet in thickness, while on interchannel areas it may be thin or entirely disappear within a few hundred yards of the deep channels. Thus a markedly disconformable contact occurs between the Berea and the underlying Bedford shale.

In central Ohio the Berea varies from 5 to 65 feet in thickness and in southern Ohio from 20 to 30 feet (see section in Table 8). The component beds in both central and southern Ohio are thin, ranging from less than an inch to 20 inches in thickness. Not uncommonly thin layers of gray shale appear at the base of the Berea in these portions of the state.

Characteristic of the Berea sandstone are abundant oscillation and current ripple marks which are very persistent in direction, the crests and troughs trending generally northwest-southeast throughout its outcrop area. They have been fully described by J. E. Hyde,[3] who suggested that the uniformity in direction is because they formed parallel to the shoreline, the direction of the ripples giving the trend of the shoreline.

The Berea is essentially unfossiliferous, broken-shell fragments, fish and plant remains being found but rarely.

[2] F. Foreman and H. L. Thomsen, "Textural and Shape Variation in the Berea Sandstone of Ohio," *Jour. Sed. Pet.*, Vol. X (1940), pp. 47–57.

[3] "The Ripples of the Bedford and Berea Formations of Central and Southern Ohio," *Jour. Geol.*, Vol. XIX (1911), pp. 257–70.

SUNBURY FORMATION

The black shales composing the Sunbury formation, which was named by L. E. Hicks in 1878 from outcrops near Sunbury, Delaware County, Ohio, lie beneath the Cuyahoga formation and above the Berea formation. The Sunbury is a black, fissile, thinly laminated, carbonaceous shale, commonly iron stained. The basal few inches contain numerous megascopic and microscopic fossils.

This shale crops out along the western margin of the Mississippian rocks exposed in Ohio, and by virtue of considerable topographic relief between Chillicothe, Ross County, and the Ohio River in southern Ohio the Sunbury outcrops can be traced for some 20 miles east from the western boundary of the Mississippian outcrops. Very few outcrops of the Sunbury occur north of southern Delaware County in central Ohio to Huron County because of the low topographic relief and the heavy cover of glacial drift. Throughout northeastern Ohio the Sunbury shale is not distinguishable from the overlying Orangeville shale member of the Cuyahoga formation. For this reason the Sunbury formation is not recognized east of Huron County, Ohio.

In central and southern Ohio the Sunbury formation varies in thickness from 15 to 30 feet. Along the Ohio River it is typically 15–20 feet thick.

CUYAHOGA FORMATION

J. S. Newberry proposed the name "Cuyahoga formation" in 1871. It includes a complex sequence of shales, sandstones, and conglomerates lying above the Sunbury shale and beneath the Logan formation. These reach a maximum thickness of slightly more than 300 feet. The Cuyahoga has been traced throughout the entire outcrop area of the Mississippian rocks of Ohio from Ashtabula and Trumbull counties on the northeast westward and southward to the Ohio River in Scioto and Adams counties.

The outstanding problem of the Cuyahoga is one of subdivision into facies and members. Each facies is a lithologic unit in which there is little or no textural change laterally. Also, owing to localized conditions of deposition, the sediments show a general uniformity in lithology vertically within a given facies. However, on the basis

TABLE 2

THE CLASSIFICATION OF FORMATIONS, MEMBERS, AND FACIES OF LOWER MISSISSIPPIAN ROCKS IN OHIO

LOGAN FORMATION *Vanceburg siltstone**		*Scioto Valley shale**		*Pretty Run sandstone**			
Vinton sandstone† Churn Creek siltstone and shale† Vanceburg siltstone† Rarden shale† Buena Vista sandstone†		Vinton sandstone† Portsmouth shale† Buena Vista sandstone†		Rushville shale† Vinton sandstone† Allensville conglomerate† Byer sandstone† Berne conglomerate†			
CUYAHOGA FORMATION *Henley shale**	*Hocking Valley conglomerate**	*Granville shale**	*Toboso conglomerate**	*Killbuck shale**	*River Styx sandstone**	*Tinkers Creek shale**	
Henley shale†	Black Hand conglomerate† Fairfield sandstone† Lithopolis siltstone†	Black Hand siltstone† Raccoon shale†	Black Hand conglomerate† Pleasant Valley shale and sandstone†	Black Hand shale† Armstrong sandstone† Burbank shale and sandstone†	Black Hand sandstone† Armstrong sandstone† Rittman conglomerate submember	Meadville shale† Sharpsville sandstone† Orangeville shale† Aurora sandstone submember	
SUNBURY FORMATION							
BEREA FORMATION							
BEDFORD FORMATION							

* Facies. † Member.

of slight changes of composition, texture, or structure, the facies are subdivided vertically into lithologic members, which can be traced laterally over much or the whole extent of the facies. Only in the areas of transition from one facies to an adjacent one is there much change in lithology.

This type of subdivision of the Cuyahoga formation was suggested and begun by Hyde in 1915.[4] The writer, while modifying some of Hyde's classifications, is continuing this system throughout the Cuyahoga in Ohio. Each facies at any one place includes the entire vertical thickness of the formation, whereas seven shale and conglomerate facies, in alternating geographic bands, comprise the outcrop area of the Cuyahoga formation (Fig. 2).

The Vanceburg facies occupies the southwesternmost part of the Cuyahoga outcrop area in Ohio in eastern Adams, Pike, western Scioto, and southern Ross counties. It includes in ascending order the following members: the Henley shale, Buena Vista sandstone, Rarden shale, Vanceburg sandstone, and Churn Creek member. The Scioto Valley shale facies, composed of the Henley shale, Buena Vista sandstone, and Portsmouth shale, crop out to the east along the Scioto River Valley in south-central Ohio.

In 1921, however, Hyde[5] correlated the Buena Vista sandstone with the Berne member of the overlying Logan formation, thus including in the Logan formation the Buena Vista and all overlying members formerly in the Cuyahoga formation. The present writer agrees with this correlation; thus only the Henley member is considered to represent the Cuyahoga formation in both the Vanceburg and the Scioto Valley facies. Therefore, it is herein proposed to retain all the members defined by Hyde in 1915 in their respective facies, with the exception of the Henley member, and to include the Vanceburg and the Scioto Valley facies in the Logan formation instead of in the Cuyahoga formation. The Cuyahoga of this area, therefore, is limited to one facies only, the Henley shale facies, which consists of one member, the Henley shale. The lithology, paleon-

[4] "Stratigraphy of the Waverly Formations of Central and Southern Ohio," *Jour. Geol.*, Vol. XXIII (1915), pp. 655–82, 757–79.

[5] "Geology of Camp Sherman Quadrangle," *Ohio Geol. Surv.*, Bull. 23 (4th ser., 1921), pp. 49–90.

tology, and type localities of this and the following facies and members of the Cuyahoga and Logan formations will be treated at length later in this paper.

The Hocking Valley conglomerate facies as defined by Hyde in 1915 crops out northeast of the Henley shale facies outcrop (Fig. 2). Four members were here differentiated by Hyde: the basal Lithop-

FIG. 2.—Map showing the location of the facies of the Cuyahoga formation

olis member, the overlying Fairfield member, the Black Hand member, and the uppermost Berne member. In 1921 Hyde placed the Berne with the Logan formation. The basal and uppermost members of the Hocking Valley conglomerate facies are emended by the writer to "Lithopolis siltstone member" and "Black Hand conglomerate member," respectively.

The Granville shale facies of central and southern Licking County was described briefly in 1915 by Hyde, who distinguished the Raccoon member, the overlying Black Hand member, and the topmost Berne member. The latter, Hyde placed in the Logan formation in 1921. The present writer has traced this facies to the northwestward

into southwestern Richland and southeastern Crawford counties (Fig. 2). The two members of this facies are changed to the "Raccoon shale member" and the "Black Hand siltstone member," respectively.

The Toboso conglomerate facies as described in 1915 by Hyde is exposed in eastern Licking County. It consists of the upper Berne member, included in the Logan formation in 1921 by Hyde, the underlying Black Hand member, and a possible basal unnamed member. Field work by the present writer has extended the outcrop zone of the Toboso facies northwestward through eastern and northern Knox County into south-central Richland County. For the beds underlying the Black Hand member, which is emended to the "Black Hand conglomerate member," the writer proposes the new name, "Pleasant Valley member."

Northeast of the Toboso conglomerate facies outcrop, the Killbuck shale facies, heretofore unnamed, is exposed (Fig. 2). The members of this facies in ascending order are the Burbank, the Armstrong, and the Black Hand members, defined and described by G. W. Conrey in 1921.[6] The designations of the latter two members are changed by the writer to "Armstrong sandstone member" and "Black Hand shale member," respectively.

In the eastern half of Wayne County and in southern Medina County there is exposed the newly named "River Styx" sandstone facies which consists of the Black Hand conglomerate member and the underlying Armstrong sandstone member. The latter includes the Rittman conglomerate submember first described by Conrey in 1921.

United States Geological Survey usage assigns to the Cuyahoga in northeastern Ohio the rank of group, subdivided into the three formations—the Orangeville, Sharpsville, and Meadville. Inconsistently enough, however, the Survey has given the Cuyahoga strata of Pennsylvania the rank of formation and its Orangeville, Sharpsville, and Meadville divisions each the rank of member.

All the Cuyahoga strata northeast of the River Styx facies outcrops are now included in the new Tinkers Creek facies, which is subdivided in ascending order into the Orangeville shale and the

[6] "Geology of Wayne County," *Ohio Geol. Surv.*, Bull. 24 (4th ser., 1921), pp. 49–9 ó

included Aurora submember, Sharpsville sandstone, and Meadville shale members. The Tinkers Creek facies crops out in Ohio from Lorain and northern Medina counties to the Ohio-Pennsylvania boundary in southeastern Ashtabula and northeastern Trumbull counties (Fig. 2).

THE HENLEY SHALE FACIES

The Henley shale facies consists of but one member, the Henley shale, named by Hyde in 1915 from Henley, Scioto County. There is considerable variation in the thickness of this shale. It is thinnest along its western outcrop zone in western Scioto, Pike, Ross, and eastern Adams counties, and thickens northeastward from $5\frac{1}{2}$ feet to a maximum of 200 feet in east-central Pike County.

The Henley shale along its western outcrop zone consists of alternating red and gray argillaceous to silty, nonfossiliferous shales, but to the east, where it is thickest, the red color disappears. There is no evidence of a disconformity between it and the underlying Sunbury shale.

THE HOCKING VALLEY CONGLOMERATE FACIES

The Lithopolis sandstone member.—The Lithopolis member of the Hocking Valley conglomerate facies was named by Hyde in 1915 from outcrops near Lithopolis, Fairfield County. This member consists essentially of gray-blue, fine-grained, unevenly bedded sandstones interbedded with gray arenaceous shales. Weathered surfaces frequently are stained tan or brown. Inasmuch as its contact with the overlying member is everywhere covered, the maximum thickness of the Lithopolis can only be estimated to be between 180 and 200 feet. Exposures of the member are limited to northwestern Fairfield, southeastern Franklin, and southwestern Licking counties.

The Fairfield sandstone member.—The Fairfield member, which takes its name from outcrops in Fairfield County, overlies the Lithopolis and is exposed in Fairfield and Hocking counties. Thick coarse- and medium-grained sandstones alternating with shale layers, commonly of equal thickness with the sandstones, are distinctive of this member. The sandstones vary in color from gray to buff, tan, brown, and red-yellow; most commonly they are yellow-brown on both weathered and fresh surfaces. Each of these sandstone layers may be as much as 65 feet thick.

Because the Fairfield sandstones and fine conglomerates are similar in color and texture to the beds of the overlying Black Hand conglomerate member, the two members are easily confused, and their contact is difficult to recognize. The Fairfield sandstones not infrequently occur as thin-bedded, rather platy layers which break easily along joints into small blocks. It is the presence of the shales in the Fairfield member that distinguishes it from the Black Hand member in the Hocking Valley conglomerate facies.

The Black Hand conglomerate member.—The Black Hand conglomerate is the most widely exposed of any of the members in the Hocking Valley facies. It is typically a bright, varicolored, coarse sandstone or conglomerate, commonly cross-bedded, with rather steeply inclined laminae within beds. Some irregular, thin zones of coarse, white quartz pebbles occur imbedded in the main mass of the sandstone. The pebbles reach a maximum of 25 millimeters in length, are well rounded, and tend to assume a discoidal shape.

Over the center of the facies the most pronounced structural feature of the Black Hand is the persistent north or northeastward inclination of the lamination planes. The inclination is generally from 10° to 20°, with only the upper 10–20 feet of the member lying horizontal.

Along its western outcrop zone the Black Hand grades laterally into the shales of the Henley shale facies, but to the northeast its passage into the Granville shale facies is covered.

THE GRANVILLE SHALE FACIES

The Raccoon Shale member.—The Raccoon shale is nowhere well exposed, and its lateral and vertical extent are unknown. Generally it consists of blue-gray or brown, thinly bedded shale, sometimes stained a reddish-brown, containing thin, blue-gray and brown, fine-grained sandstone and siltstone lenses. Most of the Raccoon outcrops are along Raccoon Creek and Moots Run in central Licking County.

The Black Hand siltstone member.—The Black Hand siltstone is well exposed in the east-central part of the facies in eastern Granville and western Newark townships, Licking County. Elsewhere it is either lost by erosion or covered by glacial drift. A typical section is the one at the "Dugway."

TABLE 3

SECTION AT THE "DUGWAY" ON OHIO HIGHWAY 16, 1¾ MILES WEST OF THE NEWARK CITY LIMITS

	Feet	Inches
LOGAN FORMATION		
Byer member:		
Tan-brown, thin-bedded, medium- to coarse-grained sandstone, beds 1–3 inches thick	36	5
Berne member:		
Yellow-tan to brown, fine gravel conglomerate, becoming finer grained upward	1	5
Yellow-tan, coarse, friable sandstone	2	1
Red-brown to yellow, massively bedded, slightly fossiliferous sandstone. The lower 1 foot is a very coarse conglomerate of quartz pebbles. Near the top of the interval are thin, olive-tan, silty shales	8	4
CUYAHOGA FORMATION		
Black Hand member (altitude at the base approximately 860 feet A.T.):		
Gray, fissile shale and thin layers of gray, brown, and tan siltstone	2	5
Tan-gray, massive, cross-bedded, medium-grained sandstone	3	6
Gray to tan, nodular, finely laminated shale and fine-grained sandstone weathering dark brown	4	
Gray to brown, medium-grained, massive sandstone	8	5
Brown-gray, thin sandstone with gray, fissile shale layers	12	2
Gray-tan, cross-bedded layer of sandstone weathering brown	3	5
Gray-brown to red-brown, medium to coarse-grained, finely laminated sandstone with dark surface stain, each layer thin and changing rapidly in thickness laterally	20	10
Light-gray, tan-brown and purple, fine-grained sandstone, somewhat cross-bedded and grading laterally into thin silty layers	3	
Gray-green and gray-black, thin shales and thin brown, medium- to fine-grained sandstone layers interbedded. There is some carbonaceous matter in the sandstone	7	7
Covered	8	
Yellow-brown, thinly bedded, finely laminated, fine-grained sandstone. A few thin, gray shale layers	10	
Raccoon member:		
Blue-gray, thinly bedded shale weathering reddish-brown, containing a few gray, thin, sandy lenses and brown concretion lenses	5	6

THE TOBOSO CONGLOMERATE FACIES

The Pleasant Valley member.—The Pleasant Valley member is named by the writer from exposures northwest of Pleasant Valley School on the north valley wall of a tributary of Clear Fork in SW. Sec. 5, T. 20 N., R. 19 W., Richland County. It is a gray-buff shale containing thin layers of medium-grained sandstone. In only a few places is the basal Pleasant Valley member exposed, and at such localities only the upper few feet are seen. About 15 feet of the

TABLE 4

SECTION IN SW. COR. SEC. 5, T. 20 N., R. 19 W.
RICHLAND COUNTY

	Feet
CUYAHOGA FORMATION	
Black Hand member (altitude at the base approximately 1,278 feet A.T.):	
White to yellow-brown, gray-brown, and dark-brown coarse, quartz sandstone, with a very few, very thin, gray, argillaceous shale layers. Bedding is generally rather thin. Some of the layers are friable	36
Pleasant Valley member:	
Gray-buff shale with buff-gray, thin, medium-grained sandstone layers	16
Gray-buff, medium-grained sandstone	1
Gray-buff shale	1

Pleasant Valley member are exposed along the south bank of the Licking River east of Newark, Licking County, where it consists of massive tan siltstones, grading to tan and gray arenaceous shale with lenses of medium-grained sandstone.

The Black Hand conglomerate member.—The Black Hand member is a massive, very resistant, highly cross-bedded conglomerate and coarse sandstone from 50 to 100 feet in thickness, containing numerous quartz pebbles $\frac{1}{4}$–$\frac{1}{2}$ inch in diameter. The best exposures are at the type locality in the Black Hand gorge of the Licking River in Licking County.

The color of the Black Hand member is usually buff or yellow-brown, but at some places there are various shades of red and lavender. In northern Knox, southern Richland, and western Ashland

counties the member is a dark-brown to tan, coarse, friable sandstone.

The lamination planes in the upper 15 feet are nearly horizontal, but below they have a general inclination from 5° to 15° to the north and northwest on the southwestern side of the outcrop area, and from 10° to 15° north and northeastward on the eastern side of the Toboso facies.

THE KILLBUCK SHALE FACIES

The Burbank member.—The basal member of the facies is the Burbank, composed of a series of alternating gray arenaceous shales and buff-gray, fine-grained sandstones and siltstones with a maximum exposed thickness of 150 feet. Since the base of the member is not exposed, its total thickness is not known. The individual shale and sandstone layers rarely exceed 15 inches in thickness and generally are from 2 to 10 inches thick. The Burbank has been described in detailed sections by Conrey.[7]

The Armstrong sandstone member.—Above the Burbank member in the Killbuck facies is the Armstrong sandstone member, consisting of buff, gray-buff, and yellow-buff, fine-grained sandstone with a few interbedded, thin, gray shale layers. The lower sandstone layers are 1–2 feet thick, while the upper layers reach 3–8 inches. Typical sections may be measured in Killbuck Valley and Cedar Run Valley near Overton, Wayne County. The thickness of the Armstrong averages from 30 to 35 feet and reaches a maximum of 50 feet. It is difficult to determine the exact stratigraphic equivalent of the Armstrong member in the Toboso comglomerate facies, but it is probable that the Armstrong sandstone of the Killbuck facies is equivalent to the basal part of the Black Hand conglomerate of the Toboso facies.

The Black Hand shale member.—Overlying the Armstrong member in the Killbuck facies is the Black Hand shale, which has a total thickness of 75–80 feet. In this facies the Black Hand consists almost entirely of gray-blue shale, with sandstone layers only in the basal 10–20 feet. Generally very thin, the sandstones are fine grained and have a gray-brown color. The upper part of the member

[7] *Ibid.*

may contain concretionary lenses 1–1½ inches thick. Exposures of the Black Hand in this facies are displayed in western Wayne County, since eastward the shales grade laterally into coarse sandstones

TABLE 5

SECTION IN CEDAR RUN VALLEY NORTHWEST OF OVERTON, WAYNE COUNTY

	Feet	Inches
LOGAN FORMATION		
Byer member:		
Gray to brown, fine- and medium-grained sandstone	50	
Berne member (altitude at the base approximately 1,015 feet A.T.):		
Brown, coarse sandstone containing fine gravel	5	
Gray-brown, medium-grained sandstone	10	
Dark brown, fine to coarse gravel conglomerate	1	3
CUYAHOGA FORMATION		
Black Hand member:		
Gray and gray-blue arenaceous shale containing many concretionary lenses	60	
Buff, fine-grained, massive sandstone	4	
Gray-blue arenaceous shale with some thin sandstone layers	6	
Armstrong member:		
Yellow-buff, medium-grained sandstone with a few layers of arenaceous, gray shale	20	
Gray, medium-grained sandstones 1–2 feet thick with interbedded arenaceous shales 1–3 inches thick	11	
Brown, medium-grained sandstone	1	
Gray-buff, medium-grained, thin-bedded sandstone with thin shale partings	4	
Gray-buff, massive, thick-bedded sandstone	5	
Buff, fine-grained sandstone	8	
Burbank member:		
Gray arenaceous shale and thin, brown and gray, medium-grained sandstone	20	

and conglomerates of the Black Hand member of the River Styx facies.

THE RIVER STYX CONGLOMERATE FACIES

The Armstrong member.—The basal Armstrong sandstone member is not well exposed. It consists essentially of thinly bedded, gray to brown, fine- to medium-grained sandstones interbedded with

gray and red argillaceous shales. Within the Armstrong is a layer of about 2 feet of brown and tan, coarse conglomerate, which is fossiliferous and rather friable, overlying a dark olive, medium- and coarse-grained sandstone containing considerable mica. This sandstone and conglomerate compose the Rittman conglomerate submember, named by Conrey[8] for exposures near the town of Rittman in northeastern Wayne County. The Rittman conglomerate is not traceable throughout the facies but has enough areal extent to merit ranking as a submember within the Armstrong.

The Black Hand sandstone member.—The Black Hand sandstone member crops out in the eastern part of Wayne County. Coarse, yellow sandstones with a few thin, gray shales constitute its upper 20 feet. Beneath are medium-grained, brown and gray sandstones and thicker shales. Detailed sections and descriptions have been given by Conrey.[9]

THE TINKERS CREEK SHALE FACIES

The Orangeville shale member.—The basal member in the Tinkers Creek facies is the Orangeville shale, named by I. C. White from outcrops at Orangeville, Trumbull County, on the Ohio-Pennsylvania boundary. This is a blue-gray to black shale containing very few sandstone lenses. Well exposed in Lorain and Cuyahoga counties, it is traceable from Lorain County eastward through the Mississippian outcrop zone into Pennsylvania. The basal portion of the Orangeville is equivalent to the Sunbury shale of central and southern Ohio, and the basal few inches, like the Sunbury shale, contain an abundance of small brachiopods, chiefly of the genera *Lingula* and *Orbiculoidea*. From 5 to 15 feet above the base of the Orangeville is a sandstone which is persistent throughout Cuyahoga County and the margins of surrounding counties. This is the Aurora submember, named the "Aurora sandstone member" by Prosser.[10] It is a gray-blue, fine-grained sandstone or sandstones, with interbedded gray-blue shales in places. The thickness varies from $1\frac{1}{2}$ to $8\frac{1}{2}$ feet.

Above the Aurora submember are from 100 to 150 feet of gray to dark gray-blue soft, thinly laminated shale. The best exposures

[8] *Ibid.* [9] *Ibid.* [10] *Op. cit.*, p. 211.

of this part of the Orangeville are found along Chippewa Creek west of Brecksville, Cuyahoga County.

The Sharpsville sandstone member.—The Sharpsville sandstone member was named by I. C. White from outcrops near Sharpsville, Mercer County, Pennsylvania. In the Tinkers Creek facies blue, fissile shales alternate with thin, blue to gray, fine-grained sandstones 1–3 inches thick and thinly laminated, gray, sandy shales, which in turn are overlain by alternating gray, thin sandstones and gray arenaceous shales containing poorly preserved fossils. With the fossils there may commonly be associated a considerable amount of marcasite and sphalerite. The thickness of the Sharpsville varies from 30 to 50 feet.

Separating the Sharpsville from the underlying Orangeville member, there may be a basal thin, gray-blue sandstone layer in the former member. Where such a sandstone layer is absent the underlying Orangeville merges gradually upward into the Sharpsville member. At the top of the Sharpsville the sandstones grade upward into gray, sandy shales of the Meadville member without a sharp boundary between the two.

The Meadville shale member.—The Meadville shale was named by I. C. White from exposures near Meadville, Crawford County, Pennsylvania. In the lower part of the Meadville blue-black, argillaceous, fissile shales and blue-gray, thin, laminated, arenaceous shales make up the bulk of the deposit. Some thin, blue-gray, micaceous, fine-grained sandstones are interbedded with the shales, and in addition there are numerous layers of blue, limy concretions some of which are fossiliferous.

The number and thickness of the sandstone layers increase in the upper portion of the Meadville until the sandstones make up as much of the deposit as the shales. Also in this part of the member are thin beds of blue-gray sandy limestone or calcareous sandstone weathering to a brown sandstone. The Meadville is much more fossiliferous than the underlying members of this facies.

Best exposed in Ohio in Cuyahoga and northeastern Medina counties, the thickness of the member increases from less than 100 feet in eastern Cuyahoga and northwestern Summit counties to over

200 feet in southwestern Cuyahoga and northeastern Medina counties.

LOGAN FORMATION

The Logan formation directly overlies the Cuyahoga formation and is in turn overlain in Ohio by the basal Pennsylvanian Pottsville formation except in the south-central portion of the state where, at a few places at the easternmost outcrops of the Mississippian, the Maxville limestone lies between the Logan and the Pottsville. Buff to gray, fine-grained sandstones, siltstones, and thin shales constitute the bulk of the Logan deposits, and laterally persistent thin beds of conglomerate serve as good horizon-markers.

From south-central Ohio the Logan extends northward with varying thickness to Holmes and Wayne counties, where it thins rapidly due to erosional beveling. In northeastern Wayne County and southern Medina County it pinches out entirely, and the Pennsylvanian rests directly upon the Cuyahoga formation.

Hyde in 1915 subdivided the Logan formation into three members: the Byer, Allensville, and Vinton, with the possibility of a fourth at the top, the Rushville member. In 1921 he changed the classification of the Berne from the top of the Cuyahoga to the base of the Logan formation. At the same time Hyde correlated several members previously included in the Scioto Valley and the Vanceburg facies of the Cuyahoga with the lower members of the Logan farther east. It is proposed in this work to subdivide the Logan into three facies, in a manner similar to the subdivision of the Cuyahoga. Both the Scioto Valley facies and the Vanceburg facies are moved, without change in their areal boundaries from the Cuyahoga formation into the Logan. In so doing, the Henley member is omitted from both the Scioto Valley and the Vanceburg facies, and the topmost Vinton member is added to each of these facies. The Scioto Valley shale facies is now subdivided into the following members: the Buena Vista sandstone at the base, the Portsmouth shale, and the Vinton sandstone; the Vanceburg siltstone facies of the Logan is subdivided into five members: the basal Buena Vista sandstone, the Rarden shale, the Vanceburg siltstone, the Churn Creek member, and the Vinton sandstone.

It is herein proposed to give the name "Pretty Run" to the facies of the Logan formation lying east of the Scioto Valley shale facies outcrop. The Pretty Run facies extends from eastern Scioto County north into Wayne and Medina counties (Fig. 3). Except where they have been removed by post-Mississippian erosion, there are ordinarily four members preserving the same lithologic characters through-

FIG. 3.—Map showing the location of the facies of the Logan formation

out the Pretty Run facies. These are the basal Berne conglomerate, Byer sandstone, Allensville conglomerate, and the Vinton sandstone, each defined and described by Hyde in 1915[11] and in 1921.[12] A fifth member, defined and described as the Rushville group by E. B. Andrews in 1878,[13] is found above the Vinton sandstone in southwestern Perry County, a few miles southeast of Rushville, Fairfield County.

[11] "Stratigraphy of the Waverly . . . . ," *op. cit.*, pp. 771–79.

[12] "Geology of Camp Sherman Quadrangle," *op. cit.*, pp. 145–58.

[13] "Discovery of a New Group of Lower Carboniferous Rocks in Southeastern Ohio," *Amer. Jour. Sci.*, Vol. XVIII (3d ser., 1879), p. 137.

THE PRETTY RUN SANDSTONE FACIES

Outcrops typical of the Pretty Run facies of the Logan formation occur in east-central Eagle Township, Vinton County, near Pretty Run, from which this facies is named. The section was measured at the type locality (Table 6).

TABLE 6

SECTION IN SE. SEC. 22, NE. SEC. 26, AND NW. SEC. 25
T. 10 N., R. 19 W., VINTON COUNTY

	Feet	Inches
POTTSVILLE FORMATION (PENNSYLVANIAN)		
Coarse, white sandstone	15	
LOGAN FORMATION		
Vinton member:		
Sandy, gray, yellow-buff, and red shales with a few layers of buff, medium- to fine-grained sandstone	55	
Allensville member:		
Fine gravel conglomerate	1	
Medium-grained, buff and brown sandstone with very thin lenses of conglomerate	13	10
Well-sorted, fine-gravel conglomerate	..	9
Byer member:		
Massively bedded, buff and brown, fine- and medium-grained sandstone tending to split horizontally into thin layers	84	9
Berne member (altitude at the base approximately 835 feet A.T.):		
Massive, coarse-grained, pebbly, yellow-brown conglomerate	3	11
Medium-grained, brown sandstone	1	
Yellow-brown and gray coarse conglomerate	..	4
CUYAHOGA FORMATION		
Portsmouth member:		
Gray, slightly sandy shale	135	

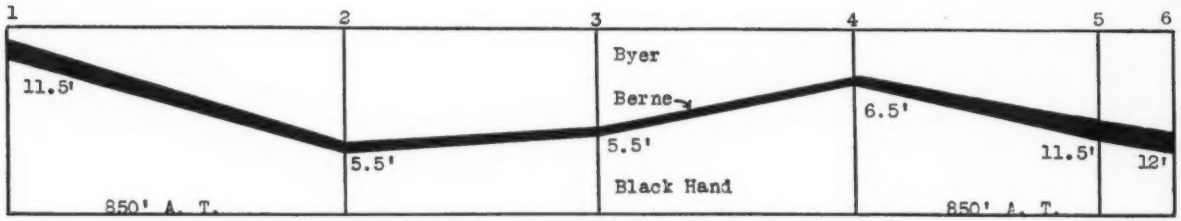
The Berne conglomerate member.—The Berne member of the Logan formation was named by Hyde from numerous outcrops in Berne Township, Fairfield County. In general, it is a basal conglomerate, composed of coarse quartz sand and quartz pebbles, well cemented with silica. Locally, fine- to medium-grained sandstone layers and shale layers are present. The thickness of the member varies from a few inches to 16 feet; commonly it is from 1 to 3 feet.

The Berne covers an uneven surface of the underlying Black Hand member. In tracing it across the area where it overlies the Toboso conglomerate facies of the Cuyahoga, the Berne is seen to rise in altitude and become thinner over the central part of the Toboso facies. Figure 4 represents a section with a constant thickness of 200 feet trending toward the southwest from Ashland County into Licking County. The shaded area represents the Berne conglomerate, between the Black Hand and the Byer members, showing its lateral variations in thickness and elevation with respect to the base of the section. As shown in this figure, along a line from Edlam, northeastern Knox County, into Licking County, the Berne rises in elevation from its position on the eastern margin of the Toboso conglomerate facies at Edlam to a maximum altitude in southern Knox County. From here it declines in altitude to the southwestern margin of the Toboso facies. Where the Berne overlies the adjoining Granville and Killbuck shale facies of the Cuyahoga there is an increase in its thickness. From Edlam north the Berne rises with regional inclination of 8 feet a mile.

Generally it can be shown that the thickest deposits of the Berne overlie the shale facies of the Cuyahoga, while it is thinnest where it overlies the conglomerate facies of the Cuyahoga. The overlying Byer, like the Berne, is thickest where it overlies areas of Cuyahoga shale deposition.

The thickness of the Berne and the Byer members where they overlie the shale facies of the Cuyahoga and their thinning where they overlie the Cuyahoga conglomerates suggest that at the time of their deposition the Cuyahoga conglomerate areas constituted topographic highs between the areas of Cuyahoga shale. Thus the sands and gravels of the Lower Logan members accumulated to a greater thickness in the low areas over the Cuyahoga shales. This relationship is somewhat complicated by the fact that in some places the uppermost Cuyahoga members of the conglomerate facies were beveled by erosion prior to initial Logan deposition.

The Byer sandstone member.—The Byer sandstone member is present throughout the Pretty Run sandstone facies. It varies considerably in thickness, measured sections showing a range from 18 to 154 feet. In general, however, there is little change in its litho-



KEY

1. SW. Sec. 34, T. 21 N., R. 15 W., Ashland County.
2. Edlam, Knox County.
3. NE. SE. Sec. 4, T. 6 N., R. 10 W., Knox County.
4. Sec. 8, T. 4 N., R. 11 W., Licking County.
5. Horn's Hill, northcentral Newark Township, Licking County.
6. "Dugway," southwestern Newark Township, Licking County.

Horizontal scale:
1 inch = 7 miles.

Vertical scale:
1 inch = 180 feet.

The thickness of the Berne, which has been exaggerated, is designated at each locality.

FIG. 4.—Vertical cross section showing variations in thickness and elevation of the Berne conglomerate across the Toboso conglomerate facies from Ashland County into Licking County, Ohio.

logic character. Buff to brown, fine- and medium-grained, rather thin-bedded sandstones prevail. Locally there are shale lenses of varying thicknesses, but there are no persistent distinctive lithologic units to relieve the monotony of the sandstone succession or to serve as key horizon-markers for the Byer throughout the Pretty Run facies.

Fossils are scattered and not abundant in the Byer sandstone. There are no fossiliferous horizons traceable over extensive areas, and in many areas the Byer is completely devoid of fossil remains.

The Allensville conglomerate member.—The Allensville conglomerate member was named and defined by Hyde from numerous outcrops in the vicinity of Allensville, Vinton County. It is characterized by well-sorted, coarse sand or fine-gravel conglomerate. The typical size of the well-rounded quartz grains ranges from 1 to 2.5 millimeters in diameter. The color of the grains may be white to colorless, or the grains may be stained varying shades of brown or red. The beds of well-sorted conglomerate each may be as much as 6 inches thick or may be but a thin veneer less than $\frac{1}{8}$ inch thick overlying finer-grained sandstone. Associated with the conglomerate beds are shales and beds of buff sandstone of varying grain size and thickness.

The Allensville is commonly from 15 to 20 feet thick, thinning to as little as 6 inches along the southwestern margin of its area of outcrop, and reaching a reported maximum of 39 feet in Pike County.[14] It is a very persistent member and, as such, constitutes a valuable horizon-marker throughout the Pretty Run sandstone facies. From Hocking County to the northern limits of this facies the Allensville has approximately the same areal distribution as has the underlying Byer sandstone. The section (Table 7) displays a typical exposure of the Allensville in central Ohio.

Fossiliferous gray shale interbedded with the coarse sandstone and conglomerate layers is a typical association found in the Allensville from Fairfield County north into Ashland County. Stratigraphically the coarsest conglomerate beds occur most commonly at the top of the member. Geographically the coarsest material occurs in Wayne County, becoming finer in Licking and Knox counties and again

[14] Hyde, "Stratigraphy of the Waverly . . . . ," *op. cit.*, p. 775.

coarser in southern Ohio. Everywhere the conglomerate beds have a high content of iron in the form of limonite, giving the matrix material a distinctive dark-brown color not seen in the Byer or Vinton members of the Logan formation.

TABLE 7

SECTION ON EAST SIDE OF ROCKY FORK IN SEC. 8, T. 4 N. R. 11 W., LICKING COUNTY

	Feet	Inches
LOGAN FORMATION		
Vinton member:		
Buff, thin-bedded, medium-grained sandstone	49	
Gray to maroon, thin shales	10	
Allensville member:		
Yellow-brown, medium-grained sandstone	1	
Brown, medium-grained sandstone	5	
Brown, coarse-grained quartz sandstone	2	
Gray to buff somewhat sandy shale weathering red-brown to blue-brown, with interbedded buff, thin, medium-grained sandstone	4	
Red-brown to yellow-brown, well-sorted, coarse-grained, quartz sandstone, somewhat cross-bedded	5	
Byer member:		
Olive-buff, medium-grained sandstone, beds 6–12 inches thick. (A fossiliferous zone consisting mainly of crinoid stems occurs about 2 feet above the underlying shale. A few gray, argillaceous lenses and brown concretionary shale lenses are present)	11	6
Gray, somewhat sandy shale	2	
Brown, medium-grained, cross-bedded sandstone, with a few layers of brown, fissile shale and lenses of gray, medium-grained sandstone	14	6
Berne member (altitude at the base approximately 990 feet A.T.):		
Coarse basal conglomerate grading upward within 3½ feet to coarse sandstone. (The upper 3 feet consist of a fairly well-sorted quartz conglomerate. Grains are 2–3 mm. in diameter, becoming coarsest at the top)	6	6

Locally in Licking, Knox, and Wayne counties there is evidence of erosion at the base of and within the Allensville.

The Vinton sandstone member.—Comformably overlying the Allensville member in the Pretty Run sandstone facies is the Vinton sandstone member, named by Hyde from Vinton County,

where it is well exposed. The contact between the Vinton and the Allensville is always a sharp one, since the basal shale beds of the former lie directly upon the coarse sandstones and conglomerates of the latter without any gradation from the coarse to the fine deposits. This distinctive contact is persistent throughout the Pretty Run facies.

The Vinton consists largely of interbedded gray, arenaceous shales and gray to buff siltstones and fine-grained sandstones. The latter differ from those of the Byer in that they are generally gray when unweathered, whereas the Byer sandstone has a buff color. On weathered surfaces both the Byer and the Vinton sandstones are strikingly similar. A dark-yellow to yellow-brown highly fossiliferous layer, only a few inches thick and frequently used as a horizon-marker, can be found in the Vinton in many places throughout the Pretty Run facies.

The thickness of the Vinton varies considerably, owing to the fact that erosion beveled the Vinton, in places cutting rather deep valleys before Pottsville deposition began. Although its average thickness is 75–100 feet, the greatest reported thickness is 240 feet in southeastern Licking County.[15]

The Rushville shale member.—For about 0.2 mile along the road leading north from Avlon in the southwest corner of Sec. 36, T. 17 N., R. 17 W., Perry County, there are outcrops of shale, which probably correspond to the Rushville shale named and described by Andrews in this region in 1878. The Rushville member is a gray and red argillaceous shale containing a few buff, thin, sandy shale layers up to 2 inches thick. The base of the outcrop is at approximately 975 feet A.T., and coarse Pennsylvanian sandstone disconformably overlies the Rushville shale at about 1,000 feet A.T.

THE SCIOTO VALLEY SHALE FACIES

The Buena Vista sandstone member.—The Buena Vista member, first named by Orton in 1874, was defined by Hyde in 1915 to include the basal layer of the series known by quarrymen near Buena Vista, Scioto County, as the "City Ledge." Along the Scioto River Valley the Buena Vista reaches a maximum thickness of from 25 to

[15] *Ibid.*, p. 779.

30 feet. It is a white to buff and gray, medium- and fine-grained sandstone with beds up to 16 inches thick interbedded with limonitic layers and arenaceous gray to buff shale.

East of the Scioto River the sandstones grade into sandy shales which become indistinguishable from the Henley shale and the Portsmouth shale. The eastward dip of the Buena Vista in the Scioto Valley facies is very slight, owing to the considerable eastward thickening of the underlying Henley member.

The northernmost outcrops of the Buena Vista occur in southwestern Ross County, where the thickness varies from 2 to 10 feet.

The Portsmouth shale member.—The Portsmouth shale overlies the Buena Vista sandstone in the Scioto Valley shale facies. At no place north of the Ohio River are there exposures of the Portsmouth shale where it is possible to measure its entire thickness. Only rarely are the contacts between the Portsmouth and the overlying and underlying members exposed.

The thickness of the Portsmouth shale where it crops out on the bluffs of the north bank of the Ohio River at Portsmouth, Scioto County, reaches a maximum of 253 feet. Here it is a gray argillaceous to silty shale containing a few sandstone lenses.

Inasmuch as (1) the thickness of the Portsmouth shale in south-central Scioto County exceeds the greatest known combined thicknesses of the Byer and Allensville members, and (2) because the base of the Portsmouth shale is at the same stratigraphic position as the base of the Byer, while (3) the base of the massive sandstone overlying the Portsmouth is considerably higher than the westward projection of the base of the Vinton, it seems probable that the upper part of the Portsmouth shale along the Ohio River is the westward equivalent of part of the Lower Vinton sandstone member of the adjacent Pretty Run facies. For convenience the base of the Vinton member in the Scioto Valley facies is set at the base of the sandstone overlying the Portsmouth shale.

In eastern Pike and Ross counties the Portsmouth shale grades eastwardly into the Byer sandstone member of the Pretty Run facies. The change from shale to sandstone is gradual, and the zone of transition is marked by a thick series of alternating buff arenaceous shales and shaly siltstones.

The Vinton sandstone member.—The Vinton sandstone member of the Scioto Valley facies consists of fine-grained sandstone and siltstone, massive to thin-bedded, buff to yellow-brown on weathered surfaces, and light buff to gray on fresh surfaces. It is found capping the higher hills on either side of the Scioto River Valley in Scioto and Pike counties. In northern Pike County and in Ross County, Pennsylvanian sediments disconformably overlie the Vinton east of the Scioto River. Throughout the facies the thickness of the Vinton is variable, since its upper limit is a very uneven erosional surface. From Ross County southward to the Ohio River the thickness varies from 135 feet to as little as 40 feet.

THE VANCEBURG SILTSTONE FACIES

The Buena Vista sandstone member.—The Buena Vista at its type locality near Buena Vista, Scioto County, has a thickness of $6\frac{1}{4}$ feet. Here it is composed of a basal layer of light-gray to white sandstone $2\frac{1}{4}$ feet thick overlain by 6 inches of shale and an upper sandstone layer $3\frac{1}{2}$ feet thick. Along its westernmost outcrop zone it varies from 1 to 6 feet in thickness. Where only 1 or 2 feet thick, it consists commonly of but one layer of light-gray siltstone and fine-grained sandstone. Eastward in this facies the Buena Vista thickens to a maximum of about 20 feet, as shown in the section (Table 8).

In western Jackson and Vinton counties the Berne conglomerate appears at the same horizon and in the same structural position as would the Buena Vista were the latter projected that far east with the dip which prevails in east-central Pike and Ross counties. Because of this possible equivalence of the Buena Vista with the basal Berne conglomerate, the Buena Vista is considered to be the basal member of the Logan formation in the Vanceburg and Scioto Valley facies.

The Rarden shale member.—Hyde named the Rarden member from the town of Rarden, Scioto County. It consists of red and gray argillaceous and silty shales with a variable thickness of from 25 to 30 feet. To the north and west of the outcrop area of the Vanceburg facies (Fig. 3) it has been removed by erosion, and east of the facies it grades into the gray Portsmouth shale.

The Vanceburg siltstone member.—The Vanceburg siltstone was named by Hyde from outcrops at Vanceburg, Kentucky. In general,

the Vanceburg member consists of fine-grained, buff to tan-brown sandstone and siltstone in layers 8–12 inches thick. Numerous thin, gray argillaceous shales are interbedded but make up only a small

TABLE 8

SECTION AT ELM GROVE, PIKE COUNTY

	Feet
LOGAN FORMATION	
Vanceburg member:	
Buff to tan-brown, fine-grained sandstone and siltstone in layers 8–15 inches thick, with intercalated gray, thin, argillaceous shales	59
Rarden member:	
Red and tan-gray argillaceous to arenaceous shale	31
Buena Vista member:	
White to gray-buff, medium- and fine-grained sandstone, beds up to 16 inches thick, with limonite lenses and gray and buff sandy shales	20
CUYAHOGA FORMATION	
Henley member:	
Olive-buff shale	25
SUNBURY FORMATION	
Black and brown-black fissile shale	15
BEREA FORMATION	
Gray-white, fine-grained sandstone and siltstone, beds 6 inches to 2 feet thick	26
BEDFORD FORMATION (altitude at base approximately 800 feet A.T.)	
Chocolate and olive-tan argillaceous to arenaceous shale	74
Light buff, fine-grained, thinly-bedded sandstone	20
OHIO SHALE (DEVONIAN)	

percentage of the total bulk of the member. Its thickness varies from 80 to 150 feet, although no good exposures are available to show its entire thickness in the Vanceburg facies in Ohio. Furthermore, there is no dependable horizon at which to separate the Vanceburg from the overlying Churn Creek member, distinction between the two being made on the basis of the larger sandstone content of the former.

The Churn Creek member.—The Churn Creek member was named by Hyde "from Churn Creek in the southeastern part of Adams County on the divide between which and the head of Lower Twin Creek good outcrops are seen in roadside ditches."[16] The Churn

[16] *Ibid.*, p. 763.

Creek consists of a tan, gray, and reddish arenaceous to argillaceous shale, at some places with limy shale lenses. It may be as much as 100 feet thick, but very few exposures of the Churn Creek occur in the Vanceburg facies, so that its greatest thickness and areal extent cannot be exactly determined. Its presence has not been demonstrated anywhere except in eastern Adams and western Scioto counties.

The Vinton sandstone member.—The Vinton sandstone has been located in this facies only near Buena Vista, where it is a rather massive, yellow-buff, fine-grained sandstone. Its thickness is undetermined.

CONCLUSIONS

Taking into consideration that (1) the Tinkers Creek facies has a general southward dip of 15 feet a mile and that (2) the vertical distance between the top of the Berea formation and the top of the Cuyahoga formation in the River Styx and the Killbuck facies is from two to two and a half times the vertical distance between the same horizons directly north in the Tinkers Creek facies, it appears possible that the Tinkers Creek members are all stratigraphically below the exposed members of the River Styx and the Killbuck facies. The Black Hand member of the River Styx facies is the equivalent of the Black Hand members of each of the other facies to the southwest in the Cuyahoga formation. The Armstrong member of the River Styx and Killbuck facies is probably the equivalent of the basal part of the thick Black Hand member of the Toboso facies. The Burbank member of the Killbuck facies, the Pleasant Valley member of the Toboso facies, the Raccoon member of the Granville facies, and the Fairfield member of the Hocking Valley facies may all be equivalents. The Lithopolis member of the Hocking Valley facies is similar in lithology as well as in stratigraphic position to the upper members of the Tinkers Creek facies. It may be equivalent to part or all of the combined Sharpsville and Meadville members. These correlations are made primarily on the basis of stratigraphic position and structure, since the fossil content of many of the various members is too scanty and poorly preserved for reliable correlation.

The axes of each of the conglomerate facies, i.e., the Hocking Valley, Toboso, and River Styx facies, have a general north-northwest–

south-southeast trend, which is in contrast to the more nearly northeast-southwest trend of the Mississippian outcrops in Ohio. Without exception the conglomerate facies are thicker than the shale facies. Of particular structural importance is the fact that except in the uppermost few feet the lamination planes in each of the conglomerate facies dip northeast 10°–30° on the northeast and east flanks of the facies. The dip of the laminae on the west flanks of the facies is west to northwest 5°–15° and north and northwest 5°–10° along the axial portion of each of the conglomerate facies. The topmost beds are essentially horizontal. The westward dips are less in degree than the eastward dips, owing to regional tilting to the eastward.

Each conglomerate facies becomes narrower in lateral extent in progressing northwestward, whereas each shale facies is wider in that direction (Fig. 2). This, together with the fact that the conglomerates become finer grained to the northwest and dip west, northwest, north, and east, suggests that the material was derived from lands to the southeast.

It is apparent that any strong shore current or wave action would have spread the gravel and sand deposits alongshore laterally from the long axes of the facies. Thus the conglomerate facies would not have formed the existing distinct bodies which are fairly sharply defined from the shale facies. This condition and the presence of abundant irregular cut-and-fill type of cross-bedding in the conglomerates and sandstones suggests deposition under the influence of strong currents at or near river mouths. Protected areas of rather deep water must have obtained where the most steeply dipping, laminated conglomerates were deposited. Where cross-bedding is of only a few inches in magnitude or is absent, it is probable that the sediments were deposited under the influence of shore and wave currents with stream currents relatively unimportant.

Were it not for the fact that only marine fossils are present in these conglomerates, they doubtless would be regarded as essentially nonmarine. A possible explanation of these puzzling Cuyahoga sediments is that they are delta deposits laid down in marine waters, cross-bedded by the continuation of river currents into a shallow sea, and not greatly influenced by wave action or shore currents. Such coarse materials could be deposited in deltas by streams of consider-

able volume, steep gradient, and relatively short courses. Evidence seems to indicate that all the Cuyahoga conglomerate facies were deposited simultaneously and parallel to each other.

The shale facies which alternate laterally with the conglomerate facies represent areas of accumulation of fine sands, silts, and clays. These facies appear from their fossil content to be marine, and they are not so thick as the conglomerate facies.

As stated in the discussion of the Henley facies, the Henley shale is the only member in this facies and represents the extent of deposition in this area during all or part of Cuyahoga time. The westward thinning of the Henley may mean that the Cincinnati arch was a topographic feature of some importance when the Henley was deposited.

No axial trend for the Pretty Run facies of the Logan formation can be determined (Fig. 3), since most of the northern and all of the eastern and southern boundaries are covered. The Scioto Valley shale facies has a long axis trending north-south. To its west the Vanceburg siltstone facies is elongate north and south, but the western margin of this facies has been lost by erosion.

The relatively widespread areal extent of the Pretty Run facies, together with the fact that there are no important lithologic changes laterally in any of its members, whereas vertically there are conspicuous contrasts in lithology, suggests that from time to time in the Pretty Run episode there was considerable change in the types of sediment being deposited in a sea in which wave action and currents sorted the materials and spread them out rather broadly.

Disconformably overlying the Cuyahoga formation, the Berne conglomerate of the Logan formation is a basal conglomerate representing coarse materials from rejuvenated erosion of adjacent lands. The Berne is somewhat thicker over the shale facies of the Cuyahoga, i.e., the areas of lesser amounts of Cuyahoga deposition, than over the conglomerate facies. The fact that the Berne, as well as the higher Allensville conglomerate, thins and disappears along the western margin of the facies in south-central Ohio indicates that the source of the materials for these and the other members of the Pretty Run facies was to the east or southeast. The deposits of the Scioto Valley and the Vanceburg facies probably came from the

south. There is no evidence of land areas to the north or to the west, and it is very likely that the sediments of Logan formation came from the same lands that supplied the material of the Cuyahoga formation.

Regionally all the Mississippian formations in Ohio dip from the Cincinnati arch in western Ohio eastward into the portion of the Appalachian trough lying west of the folded belt in Pennsylvania and West Virginia. The axis of the trough pitches to the south-southwest. Therefore, the east-southeast dips of the formations into the trough decrease from south to north along the east flank of the arch. In southern Ohio the eastward dip varies from 20 to 25 feet a mile; in central Ohio it is from 15 to 20 feet a mile. The true southeast dip of the Mississippian formations in southern and central Ohio is somewhat obscured by the eastward thickening of these formations. Across the northeastern part of Ohio the formations are essentially horizontal. Locally in Cuyahoga County there is a slight westward dip. The southward component of the southeastern dip of the strata ranges from 10 to 15 feet per mile along the eastern margin of the Mississippian outcrop zone in Ohio.

Since fossils are relatively scarce in the Mississippian rocks of Ohio and little study has been given to the faunas that have been found, correlation of these rocks with other Mississippian formations is not exact. The fossils of the Bedford formation suggest both Devonian and Mississippian affinities. In Kentucky the Bedford together with the underlying Devonian Ohio shale and the overlying Berea and Sunbury formations merge into the Chattanooga shale. Fossils of the Sunbury shale indicate its Kinderhook age. The Cuyahoga formation appears to be equivalent in age to the Fern Glen and the Burlington formations in the Mississippi River Valley. The Logan formation is the Ohio equivalent of the Keokuk (late medial Mississippian) of the Upper Mississippi Valley region.

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THE ORIGIN OF THE MIMA MOUNDS OF WESTERN WASHINGTON

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ABSTRACT

The Mima mounds occur on certain prairies of glacial outwash in western Washington. The mounds are closely spaced, round or oval, from 10 to 40 feet in diameter, and from 1 to 7 feet in height. The typical mound is a double-convex lens of loose, unstratified, black silt-gravel set in a shallow pit in stratified yellow outwash gravel. Mounds are found only where a thin layer of soil overlies a compact bed of gravel, not on deep prairie soils.

The Mima mounds are formed by pocket gophers (*Thomomys talpoides*) over long periods of time. Gopher activity in any particular place destined to become a mound site starts with intensive burrowing, such as that required in the construction of a nest, which loosens the soil and stimulates the growth of vegetation. The vegetation, in turn, furnishes food for the gophers and encourages them to concentrate their activities in the vicinity. A stage is reached where the gophers find sufficient food on the mounds to maintain them the year around, making it unnecessary for them to forage, except at rare intervals, into the intermound depressions.

In deep burrowing to create living quarters gophers dig a shallow pit in the stratified gravel beneath each mound. The smaller elements in the stratified gravel removed by deep burrowing become mixed with silt to form the substance of the mound lens. Stones too large to be moved by the gophers are undermined and settle to the bottom of the mound.

In shallow exploratory burrowing in the peripheral zone the gophers do not undermine large stones but remove soil from about them, eventually leaving them exposed on the surface of the ground.

INTRODUCTION

The Mima[1] mounds of western Washington were first reported by Charles Wilkes[2] nearly a century ago. The explorer was impressed by the flowing symmetry of the mounds and investigated them in an attempt to discover their origin, which was thought to be of an artificial nature. The many hypotheses offered in ensuing years to explain the mounds have been fully and ably summarized by J Harlen Bretz.[3]

[1] From Mima Prairie, pronounced *mī' mȧ*.

[2] *Narrative of the United States Exploring Expedition during the years 1838, 1839, 1840, 1841, 1842* (Philadelphia, 1845), Vol. IV.

[3] "Glaciation of the Puget Sound Region," *Wash. Geol. Surv. Bull. VIII* (1913), pp. 97–106.

DESCRIPTION OF THE MOUND PRAIRIES

The Mima mounds are most abundant on certain prairies formed by the outwash of the last continental ice sheet (Vashon). These mound-bearing prairies are most numerous in Thurston County but are found also in Pierce, Lewis, Grays Harbor, and Mason counties.

The mound prairies are underlain by *stratified outwash gravel*, whose materials vary in size from sand to small boulders, most of the pebbles ranging from the size of a pea to that of a walnut.[4] The thickness of the stratified gravel is unknown, but it is locally at least 50 feet, as revealed by a railroad cut on Mima Prairie.

A *silt-gravel* layer composed of fine silt, sand, and small pebbles covers the surfaces of both mound prairies and mound-free prairies. It is dark brown or black in color, contrasting strongly with the yellowish color of the underlying stratified gravel. It is rather soft, lacks stratification, and varies in depth from a few inches to several feet. The contact between the silt-gravel and the stratified gravel is usually abrupt.

The silt-gravel was doubtless laid down as an overwash by glacial streams, although any original stratification has disappeared as the result of organic action—penetration of grass roots and the burrowing of moles, gophers, and other animals. The silt is now thoroughly mixed with the gravel. The dark color is due to a high humus content and is typical of native prairie soils in the Northwest.

Vegetation on the mound prairies is sparse and is characterized by annuals, grasses, and mosses which dry up in the summer. A species of moss, *Rhacomitrium canescens* var. *ericoides*, imparts the dominant brown color to the summer landscape. Trees do not occur on the prairies except where they have invaded in recent years.

DESCRIPTION OF THE MOUNDS

The outlines of the Mima mounds are smooth and flowing, giving the impression of great spheres nearly buried in the earth (Figs. 1, 3). Their basal diameters vary from 8 to 40 feet, although on prairies where the mounds are best developed their diameters do not vary greatly from 20 feet. In height the mounds range from less than 1 foot to 7 feet. They reach their maximum size on Mima Prairie,

[4] C. C. Nikiforoff, "The Inversion of the Great Soil Zones in Western Washington," *Geog. Rev.*, Vol. XXVII (1937), p. 212.

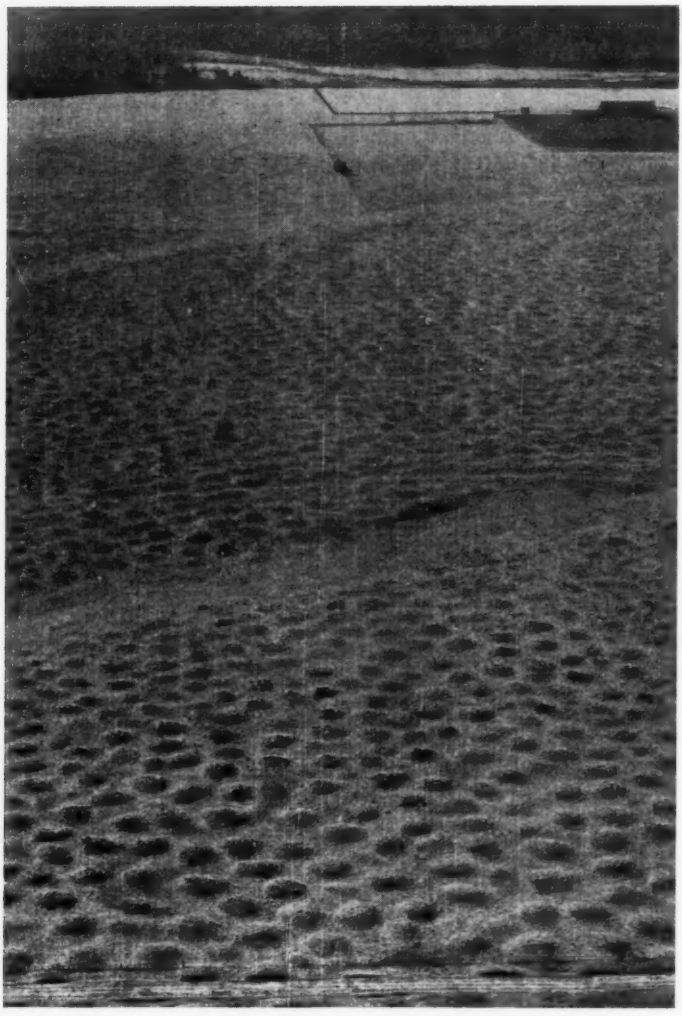

FIG. 1.—Glacial outwash prairie two miles southwest of Tenino, Washington, covered with typical Mima mounds. A shallow channel appears in the middle distance. Mound sections appear along a road cut in the foreground. March 10, 1941.

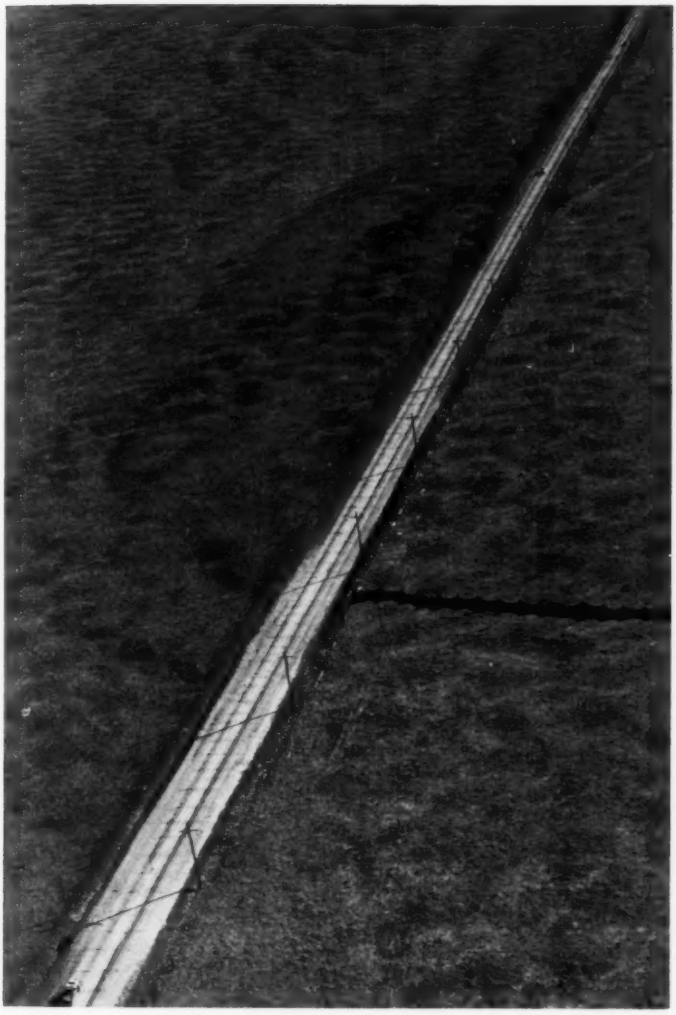

FIG. 2.—Mima mounds on outwash channels and terraces on a prairie two miles southwest of Tenino, Washington. Individual gopher "hills" appear as small dark spots on the mounds. March 10, 1941.

Thurston County—the type locality—although some mounds on Rocky Prairie, near Tenino, are nearly as large. Seen from above, the Mima mounds are round or slightly oval in shape (Fig. 2). In a few instances two mounds are joined together by a low saddle, and, very rarely, three are joined together in the shape of a rude L. Most of the mounds in any one locality are of approximately the same size.

FIG. 3.—Profile view of Mima mounds on the type locality, one and one-half miles S.E. of Bordeaux, Washington. The field in the foreground has been leveled for agricultural use. Height of mounds ranges from six to seven feet. April 18, 1941.

The symmetry and regularity of size of the mounds often give the observer an impression of regular spacing, which tends to disappear on closer inspection. There is absolutely no regularity of spacing nor are the mounds oriented in any direction. The long axes of oval mounds lie at various angles to one another and have no consistent relation to the slope of the ground. In the few triple mounds seen the two intermound saddles lay at nearly right angles to each other.

Certain other unrelated topographic features occurring on the mound prairies should be mentioned. These include channels, terraces, kettles, and Ford mounds.[5] Ford mounds are large, irregular

[5] Bretz, *op. cit.*, p. 87.

masses of gravel formed by outwash between two or more kettles and are not to be confused with Mima mounds, although in some cases there is a superficial resemblance. Ford mounds are composed of yellowish, coarse, irregularly stratified gravel, while Mima mounds are composed of unstratified black silt-gravel. A Ford mound may quickly be recognized by the fact that compact stratified gravel lies but a few inches below the surface of the mound, while in a Mima mound it lies several feet below. The surfaces of Ford mounds are often strewn with cobbles of various sizes, while cobbles never occur on the surfaces of Mima mounds.

The prairie surface between the mounds is usually not level but slopes gently, lending emphasis to the symmetrical, flowing contour of the mounds. Many intermound spaces are closed depressions, i.e., rimmed about by mounds and intermound saddles. On some prairies small but typical Mima mounds rise from a flat surface.

The intermound areas may or may not contain exposed cobbles. Where present, the *intermound cobbles* generally form an irregular layer of stones in the deep part of the depressions and are most abundant where the intermound areas are deepest. Intermound cobbles weigh up to 50 pounds but on most prairies are about the size of a football (Fig. 4).

Cross sections of Mima mounds appear along road cuts and in gravel pits (Fig. 5). The shape of the basal contact of the mounds varies with the size of the mound. The *smaller* mounds are generally double-convex lenses of silt-gravel resting in a depression in the stratified gravel. For example, on Scott's Prairie the basal convexity of the average mound is greater than the surface convexity. In *larger* mounds—as, for example, those on Rocky Prairie, Thurston County —the basal contacts dip downward only slightly in the center. The amount of curvature of the base of the mounds on any prairie seems to be inversely proportional to the average size of the Mima mounds. The low, wide mounds tend to have shallower basal convexities than high, narrow mounds. Individual variation, however, is great.

The strata of the coarse outwash gravel do not bend downward under the bases of the silt-gravel mound lenses or intermound depressions but are truncated abruptly by the latter.

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[5] Bretz, *op. cit.*, p. 87.

masses of gravel formed by outwash between two or more kettles and are not to be confused with Mima mounds, although in some cases there is a superficial resemblance. Ford mounds are composed of yellowish, coarse, irregularly stratified gravel, while Mima mounds are composed of unstratified black silt-gravel. A Ford mound may quickly be recognized by the fact that compact stratified gravel lies but a few inches below the surface of the mound, while in a Mima mound it lies several feet below. The surfaces of Ford mounds are often strewn with cobbles of various sizes, while cobbles never occur on the surfaces of Mima mounds.

The prairie surface between the mounds is usually not level but slopes gently, lending emphasis to the symmetrical, flowing contour of the mounds. Many intermound spaces are closed depressions, i.e., rimmed about by mounds and intermound saddles. On some prairies small but typical Mima mounds rise from a flat surface.

The intermound areas may or may not contain exposed cobbles. Where present, the *intermound cobbles* generally form an irregular layer of stones in the deep part of the depressions and are most abundant where the intermound areas are deepest. Intermound cobbles weigh up to 50 pounds but on most prairies are about the size of a football (Fig. 4).

Cross sections of Mima mounds appear along road cuts and in gravel pits (Fig. 5). The shape of the basal contact of the mounds varies with the size of the mound. The *smaller* mounds are generally double-convex lenses of silt-gravel resting in a depression in the stratified gravel. For example, on Scott's Prairie the basal convexity of the average mound is greater than the surface convexity. In *larger* mounds—as, for example, those on Rocky Prairie, Thurston County—the basal contacts dip downward only slightly in the center. The amount of curvature of the base of the mounds on any prairie seems to be inversely proportional to the average size of the Mima mounds. The low, wide mounds tend to have shallower basal convexities than high, narrow mounds. Individual variation, however, is great.

The strata of the coarse outwash gravel do not bend downward under the bases of the silt-gravel mound lenses or intermound depressions but are truncated abruptly by the latter.

FIG. 4.—Exposed cobbles in an intermound depression on Rocky Prairie, three miles north of Tenino, Washington. The largest cobble here weighs approximately twenty-five pounds. April 17, 1941.

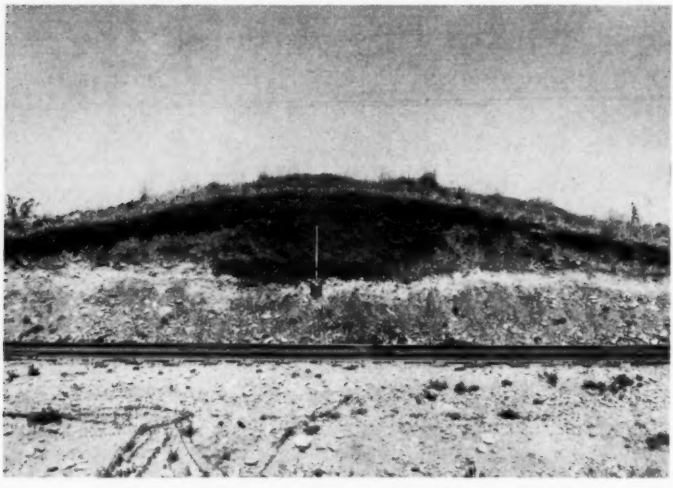


FIG. 5.—Characteristic section of Mima mound, exposed by railroad cut three and one-half miles N.N.E. of Tenino, Washington, showing lenticular body of black silt-gravel lying in bed of yellow stratified gravel. The section is about three feet in front of the vertical axis of the mound; overlying slump and vegetation have been cleared away; the shovel is five feet long overall. April 18, 1941.

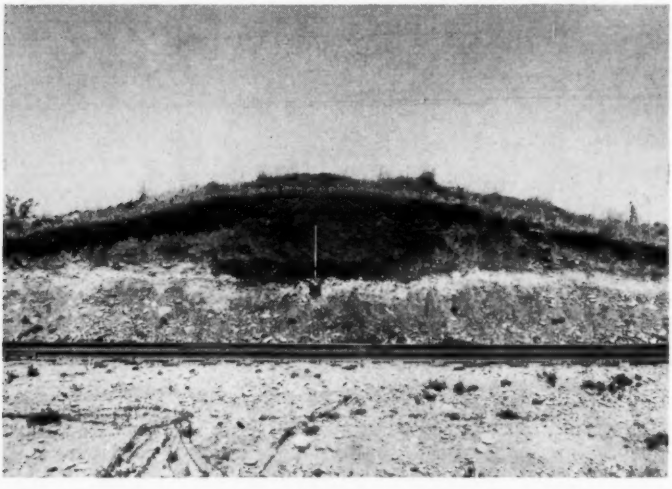
An irregular layer of *mound cobbles* often lies beneath the base of the mound lens. The mound cobble layer, as well as intermound cobbles, is found only where cobbles of approximately the same size are present in the underlying stratified gravel. Where cobbles are abundant in the latter, mound cobbles and intermound cobbles are abundant. Where cobbles are scarce or absent in the local stratified

FIG. 6.—A Mima mound "root" along the basal contact of black silt-gravel and yellow stratified gravel, exposed by a road cut on Mima Prairie. The root lies halfway between the vertical axis of the mound and the edge of the mound; it is four feet below the surface of the mound; the scale mark is one foot long. April 18, 1941.

gravel, mound cobbles and intermound cobbles are correspondingly scarce or absent.

The basal contact of the Mima mound is irregular. Here and there small extensions of silt-gravel project downward into the stratified gravel (Fig. 6). These extensions are roundish in cross section and vary from 2 to 6 inches in diameter. They twist and turn, some of them at right angles. They do not taper to points but end with flat or bluntly rounded ends. Rarely the terminus is distinctly swollen. Some of them lead from the mound into the stratified gravel and up

FIG. 4.—Exposed cobbles in an intermound depression on Rocky Prairie, three miles north of Tenino, Washington. The largest cobble here weighs approximately twenty-five pounds. April 17, 1941.



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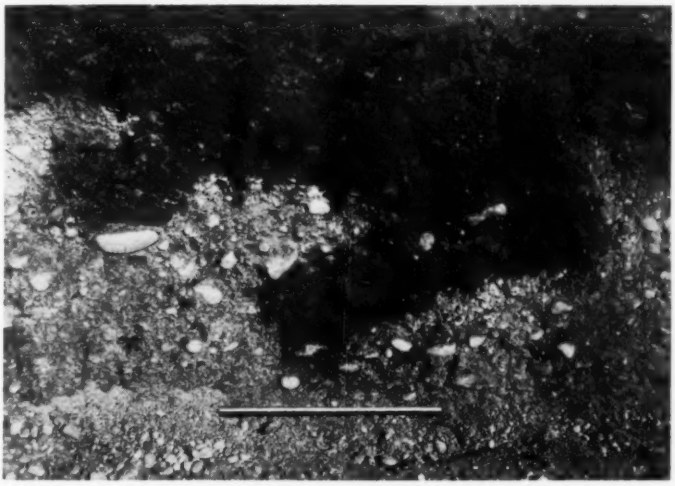

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again into the mound without ending. These extensions were referred to by Bretz[6] as "mound roots."

PRESENT THEORY OF ORIGIN

We deduce that the Mima mounds have been formed by the localized activities of pocket gophers (*T. talpoides*) over thousands of years. We have seen what we consider developmental stages of "growing" mounds, i.e., mounds in the process of formation at the present time, as well as fully formed or "mature" mounds. The essential conditions necessary for the formation of Mima mounds are (1) *the presence of gophers* and (2) *a prairie area consisting of a thin layer of silt overlying a dense layer of gravel unfavorable to the growth of plant roots*.[7]

INITIATION OF THE MOUNDS

Pocket gophers presumably migrated northward into western Washington in postglacial or interglacial times to occupy extensive grasslands. The gophers in western Washington do not and apparently cannot exist in timbered areas. With the invasion and spread of forests the gophers were crowded on to the treeless outwash prairies. With a few exceptions, discussed later, pocket gophers and Mima mounds occur together.

At the close of the last ice age the outwash prairies were quite smooth (except for low-relief terraces, kettles, and channels) and were covered with a thin layer of silt overwash left by the streams of the Vashon glacier.[8] Gophers invading the prairie were restricted in burrowing to the thin upper silt layer and did not burrow extensively into the hard stratified gravel, except here and there for nesting and living quarters. Once a deep burrow was so constructed in the stratified gravel, the area penetrated thenceforth offered easier burrowing. Earth removed in digging the burrows was thrown to the surface in gopher "hills."[9] The increased depth, looseness, and water-holding

[6] *Ibid.*, p. 84.

[7] We suspect that in other parts of the country a clay hardpan or bedrock may substitute for the dense gravel.

[8] Cf. J. Hoover Mackin, "Erosional History of the Big Horn Basin, Wyoming," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), p. 826.

[9] Small piles of earth, rarely exceeding 1 cubic foot in volume, that are thrown up in a few hours or overnight.

capacity of the earth in the vicinity of the nest burrows resulted in a more flourishing growth of vegetation. The roots of this vegetation served as food for the gophers and tended to concentrate them in this vicinity. It might be argued that gophers attracted to, and therefore feeding more intensively in, the vicinity of their living

FIG. 7.—Prairie one mile southwest of Tenino, Washington, showing more luxuriant growth of vegetation on top of Mima mounds than on intermound areas. The dark-colored plant is bracken fern. Arrow indicates a gopher hill thrown up near the top of the mound. January 25, 1941.

quarters would *reduce* the vegetation rather than increase it. Actual observations, however, of mounds where gophers are actively working at the present time indicate that the vegetation *is* more luxuriant on the mounds than elsewhere in the vicinity (Fig. 7). Root-cutting by gophers is apparently not intensive enough to counteract the stimulating effect upon plant growth of a loosening of the soil by the animals.

GROWTH OF THE MOUNDS

To explain clearly the accumulation of earth on the mound sites, it is necessary to describe in considerable detail the *earth-carrying*

habits of the gopher, for the accumulation is dependent upon minute and not readily apparent differences in the rate of exchange of earth between the mounds and the surrounding areas.

When digging burrows, gophers dispose of earth in two ways: either they throw it out on the surface forming the familiar gopher hills, or they deposit it in abandoned burrows. Evidence of the latter action is best seen in areas of heavy snowfall where gophers construct burrows through the snow and subsequently fill them with earth. When the snow melts in the spring the filled burrows are exposed as long casts which attest the distance to which gophers will transport earth (Fig. 8).

When a gopher in digging a deep burrow encounters a stone fragment too large to handle, it burrows around and beneath the stone, allowing it to settle. The earth removed is eventually thrown out on the surface of the ground, thus burying the rock. The settling of stones and logs by gophers has been discussed by Joseph Grinnell.[10] This sinking of stones accounts for the layer of cobbles at the base of the mound. The largest pebble found in several fresh gopher hills examined by us weighed 137 grams. Pebbles of this size and smaller are commonly mixed throughout the silt-gravel of the mound, while larger pebbles are found in the mound cobble layer at the bottom of the lens.

Gophers construct what may be called *exploratory* burrows which radiate from the mounds. The exact reason for their construction is unknown, but they are probably made by gophers that prospect some distance into the intermound area for food before they become discouraged and turn back. On Scott's Prairie we found nineteen exploratory burrows leading out from one small "growing" Mima mound. These averaged about 10 feet in length. All were solidly plugged at the point where they entered the mound but were otherwise open. Many had partially collapsed or had been broken into by the feet of cattle, and all were obviously in disuse. Five of the nineteen were of relatively recent construction, for earth thrown out as gopher hills along their length was not yet covered with moss. Along one of these five burrows we found enough earth thrown out on the

[10] "The Burrowing Rodents of California as Agents in Soil Formation," *Jour. Mammalogy*, Vol. IV (1923), pp. 137–49.

surface as gopher hills to account for all the earth removed in tunneling. Along two others about half the earth had been brought to the surface. Of the remaining two only a trace of the earth was found exposed on the surface. Almost the entire quantity of earth removed in the construction of two burrows, and about half from two more, had actually been transported back into the mound where it was

FIG. 8.—Cast of earth formed by a pocket gopher. Dirt removed in the process of digging a ground tunnel was transferred to a tunnel in the snow, later exposed when the snow melted. Yakima Park, Mt. Rainier, Washington, July 6, 1933.

probably used to fill abandoned burrows and might, at a later date, have been brought to the surface of the mound as a gopher hill.

This shuttling of earth, long continued, accounts for the sunken contour of the intermound area and for the greatest part of the volume of the Mima mound. The volume of certain small Mima mounds, as on Scott's Prairie, where the surface of the intermound area is nearly level, is attributed primarily to the "fluffiness" of the gopher-worked soil of the mounds.

Intermound cobbles are exposed in the removal of earth to the mound. When a gopher making an exploratory burrow encounters

a stone too large to handle, it removes the earth from about the stone. Year after year earth is removed and carried to the mound, and the stone is eventually left exposed on the surface as an intermound cobble. It should be emphasized that in shallow *exploratory* burrowing the gopher has no incentive to dig under a large obstacle in its path and thus allow it to settle; in *deep* burrowing for living quarters the gopher attempts to tunnel under all such obstacles in order to reach a depth of several feet, at which this species of rodent habitually makes its nest.

The "mound roots" of Bretz are simply abandoned gopher burrows filled with earth. We have observed such roots in the stage of fresh, hollow burrows, as freshly filled burrows, and as burrows constructed and filled centuries ago by gophers long since gone from the area of the mounds.

The areal spacing of Mima mounds is about equal to the spacing of individual gopher "homes" or "territories" in other parts of the Pacific Northwest where soil conditions are such that mounds do not occur. The voluntary restriction of an individual gopher to a small area, even where food is abundant in the surrounding territory, has been mentioned by many writers.[11] We assume that the restriction is much more pronounced where surrounding areas are almost barren of food.

Where gophers are living in regions of deep soil, mounds are not formed, for burrowing is as easy in one spot as in another and nesting centers have no tendency to become fixed. Furthermore, exploratory burrows, i.e., shallow burrows radiating from a common center and shortly abandoned, seem to be formed only where gophers exist in areas rich in food plants surrounded by relatively barren areas.

We have stated that the necessary conditions for the formation of Mima mounds in western Washington are a bed of stratified gravel unfavorable and uninviting to the roots of plants, a thin layer of topsoil bearing sparse prairie vegetation, and gophers. A few supporting examples should be pointed out.

[11] Vernon Bailey, "Revision of the Pocket Gophers of the Genus Thomomys," *U.S. Dept. Agric., North American Fauna No. 39* (1915), pp. 1–25; Theo H. Scheffer, "Habits and Economic Status of the Pocket Gophers," *U.S. Dept. Agric. Tech. Bull. 224* (1931), pp. 1–27.

On Quillayute Prairie—a treeless island in the dense timber of the northwest Olympic Peninsula—there is a true, black prairie soil and an underlying bed of gravel. There are no gophers, or evidence of their former presence, in this isolated area and no Mima mounds.

On Bush Prairie, surrounding the Olympia airport and within ten miles of a mound-bearing prairie, the soil is deep and rich. Gophers are abundant here, and they do not build Mima-type mounds.

On Mima Prairie itself—the type locality of the mounds and the area in which the climax examples appear—there is, as we have stated, a typical silt-gravel layer over a thick gravel bed. In seeming contradiction to our hypothesis there are no gophers on this prairie. (Had gophers persisted on Mima Prairie to the present time their relation to the mounds would probably have been realized by earlier students.) We deduce, however, that gophers recently existed here, built the mounds, and for some unknown reason were exterminated. Gophers live on a prairie of the same geological origin about 1 mile to the southeast, separated from Mima Prairie by the Black River. The former occurrence of gophers on Mima Prairie is indicated by the evidence of silt-filled burrows or mound roots as well as by the composition of the mounds themselves. We are of the opinion that disease, a prolonged drought, a series of grass fires, or some other disaster eliminated the population and that the Black River and surrounding conifer forests have effectively prevented the reinvasion of gophers from neighboring sources.

RECAPITULATION OF EVIDENCE

Evidence that the type of microrelief known as a "Mima mound" is the concentration of soil by pocket gophers may be summarized as follows:

1. The Mima mound is constructed entirely of soil materials small enough to be moved by gophers.

2. Materials too large to be moved by gophers appear beneath the mound or in the intermound region.

3. Mound roots extending into the gravel bed correspond to the size and shape of tunnels and nest excavations occupied by living gophers, and roots have been found in various stages from the occupied burrow of a gopher to one long since abandoned.

4. Mima mounds are found only on prairies where gophers now live or quite certainly once lived but are absent from prairies which, though geologically similar, yield no traces of gophers.

5. The characteristic features of the mounds—namely, areal distribution, distribution with relation to grosser ground relief, size, and shape—are in conformity with the habits of pocket gophers.

REFUTATION OF PREVIOUS THEORIES OF ORIGIN

The lenticular shape, lack of bedding, and size of constituent materials of the Mima mounds immediately exclude the possibility of their formation through ordinary deposition by wind, water, or ice. Two modified depositional theories, however, have been considered.

Bretz[12] suggested that debris washed into pits on the surface of still or moving ice might have melted its way down and formed the mounds. Mima mounds, however, may occur on the surface of grosser types of prairie relief: on several terrace levels, *on the sides of terrace slopes themselves*, in the bottoms or on the sides of kettles or channels, or on the flanks or tops of Ford mounds (Fig. 2). In some places they actually cap the lip of a terrace slope, lying partly on the upper terrace level and partly on the slope. Elsewhere they may lie partly on the lower terrace level and partly on the slope. These factors plus the basal convexity and lack of stratification of the lens make the ice-debris theory untenable.

H. M. Eakin,[13] apparently referring to the Mima mounds, considered them to be periglacial stone-strip effects. Proof that the intermound cobbles of Mima mounds are not frost heaved is furnished by the fact that many cobbles lie a few inches beneath the surface of the stratified gravel of intermound depressions on Rocky Prairie, but between *unruptured gravel bedding*. The smoothly rounded, water-worn intermound cobbles are utterly unlike the angular, frost-shattered blocks which characterize stone strips or stone polygons. Furthermore, Mima mounds commonly occur where entire prairies are without intermound cobbles. The steep

[12] *Op. cit.*, p. 105.

[13] "Periglacial Phenomena in the Puget Sound Region," *Science*, Vol. LXXV (new ser., 1932), p. 536.

slopes upon which Mima mounds sometimes appear further invalidate the frost-heave theory.

R. C. Newcomb[14] advances an ingenious theory for the origin of the Mima mounds. Extremely cold weather causes a frozen surface silt layer to crack in huge polygons, 40–66 feet across. Thaw water enters the cracks, freezes, and expands. Further warming causes bulging of the center of the polygon. This process, long continued, results in accumulations of silt which, after the melting of the intermound ice wedges, forms the Mima mounds.

Several objections are at once apparent. First, the theory fails to account for the mound and intermound cobbles and for intermound depressions which extend down into the stratified gravel. Second, mounds could hardly have been formed at the bottoms of kettles, tops of Ford mounds, or lips of terraces in this manner. Third, widely scattered mounds, as on Scott's Prairie or in parts of Grand Mound Prairie (Fig. 7), have intermound areas composed of silt gravel 2 feet or more in depth; yet constantly widening cracks in frozen silt would extend at least to the surface of the stratified gravel, and widening of these cracks would force *all* silt to the center of the polygon. Mounds are sometimes found isolated from other mounds by more than 100 feet, yet no polygonal ridge surrounds the mound. Fourth, we cannot conceive of how double or triple mounds might be formed in this way. Fifth, the smoothly rounded intermound cobbles of rock materials most susceptible to frost shattering indicate an absence of a climate as cold as that postulated by Newcomb.

The large size of the pebbles in the mounds precludes the possibility that the latter were built by ants, although it is known that in other parts of the country ants are responsible for the construction of fairly large mounds.[15] We know of no ants in western Washington that construct earth mounds.

The mounds cannot reasonably be ascribed to the activities of prehistoric humans. A population extensive enough to account for the

[14] "Hypothesis for the Periglacial 'Fissure Polygon' Origin of the Tenino Mounds, Thurston County, Washington," *Geol. News Letter, Geol. Soc. Oregon County* (abstr.), Vol. VI (1940), p. 182.

[15] E. W. Hilgard, "The Prairie Mounds of Louisiana," *Science*, Vol. XXI (1905), pp. 551–52.

tens of thousands of mounds probably could not have been supported by the region. No traces of human artifacts have, to our knowledge, been found in the mounds. Early explorers in the Mima region found that the local Indians had no legends concerning the mounds.

Finally, the possibility that gophers have merely re-worked older mounds formed by other means must be considered. The evidence against such a hypothesis has been presented in the preceding pages, but its principal points may be summarized as follows: (1) the areal spacing of the Mima mounds is similar to that of individual gopher homes on mound-free prairies; (2) the Mima mounds have risen on slopes of varying degree on various types of greater prairie relief, indicating the virtual independence of the mounds of other topographic features; (3) no mounds of the Mima type which lack evidence of having been worked by gophers (mound roots, basal convexity, assortment of materials, etc.) have ever been found; and (4) on certain isolated prairies of western Washington, of an origin apparently kindred to that of the mound-bearing prairies but out of the range of pocket gophers, there are no mounds.

ACKNOWLEDGMENTS.—We wish to thank especially Dr. J. Hoover Mackin, of the University of Washington department of geology, who spent a day with us in the field and offered invaluable help in the preparation of the manuscript, and Major F. A. Bacher and his associates in the Ninety-first Observation Squadron, United States Air Corps, for important aerial photographs of the mound prairies. Professors Trevor Kincaid, G. E. Goodspeed, and Howard A. Coombs, of the University of Washington, have given us many helpful suggestions.

PRE-CAMBRIAN FORMATIONS AT POCATELLO IDAHO

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ABSTRACT

In the northern part of the Bannock Range, east of Pocatello, Idaho, pre-Cambrian volcanic rocks and unfossiliferous metamorphosed sedimentary formations outcrop. These include, in order of decreasing age: the Bannock volcanic formation, which is redefined; the Pocatello formation, which is defined for the first time; and the Blackrock limestone. They are overlain unconformably by the Brigham quartzite of Cambrian age. The upper part of the Pocatello formation contains newly discovered tillites and varved slates, which are correlated with similar deposits 100 miles to the south, in the Wasatch region of Utah.

INTRODUCTION

Knowledge of the stratigraphy of southeastern Idaho is at present largely based on the publications of G. R. Mansfield and, to a lesser degree, on the Hayden Survey, but none of the geologic publications concerned with southeastern Idaho recognizes that pre-Cambrian formations are exposed in that area. During three summer months of 1940 the writer made a study of the Pocatello quadrangle which proved that pre-Cambrian rocks occur immediately east of Pocatello. The contact with the overlying Cambrian was also established. The purpose of this paper is to describe and define the pre-Cambrian formations and to compare them with the nearest similar described series, which is 100 miles to the south in the Wasatch Mountains, Utah.

The area includes the northern third of the Bannock Range, which is located in the northern part of the Basin and Range Province, bordering on the Snake River plains. Both structural and topographic trends of the Bannock Range are northerly. The Portneuf River has cut a deep canyon across the range exposing the anticlinal structure of the pre-Cambrian formations. North of the river both limbs of this anticline are exposed (Fig. 2). The Cambrian formations have a general regional dip to the east of about 30°.

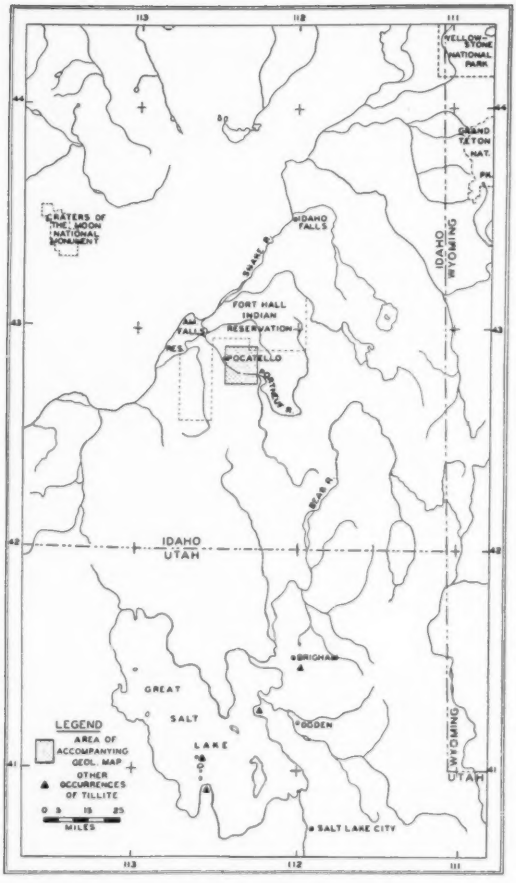

FIG. 1.—Location map showing Pocatello area and some of the occurrences of tillite in Utah.

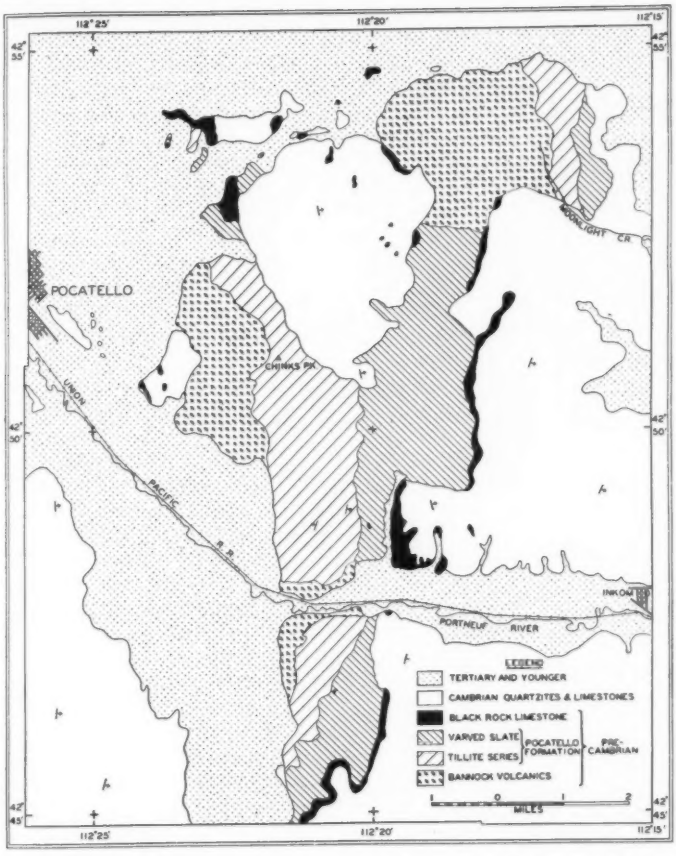

FIG. 2.—Areal geologic map of a portion of the Pocatello, Idaho, quadrangle

BANNOCK VOLCANIC FORMATION

The oldest rocks exposed in the Pocatello area are a series of metamorphosed lavas, tuffs, and volcanic breccias. F. B. Weeks and V. C. Heikes[1] first described this series but assigned it to the Ordovician and failed to observe it south of the Portneuf River. However, the present study shows this volcanic series in four separate areas. One extends along the west slope of the ridge south of the bend in the Portneuf River and eastward into the canyon along both sides of the river. The second exposure is along the west slope of the same ridge but north of the river and just west of Chinks Peak. A third, but small area, occurs northeast of Pocatello. The fourth and largest exposure is in the northeastern part of the area, at the headwaters of Moonlight Creek.

The lava is usually a dark shade of green or purple. The tuffs and breccias are lighter in color and vary from shades of green to brown. Some specimens of the lava show flow structure and parallel orientation of amygdules and mineral grains. In others, plagioclase laths have a random orientation.

Thin sections of the lavas show that quartz and plagioclase feldspar are the dominant primary minerals, while magnetite, amphibole, and pyroxene are the chief accessories. Secondary minerals are mostly micaceous, with chlorite predominating, which is in part responsible for the green color. Concentrations of chlorite in flattened aggregates parallel to the flow lines give some specimens a spotted appearance. Sericite is also abundant. Many of the amygdules have been filled with calcite and secondary iron oxide. Although the breccias vary greatly in composition, most of the larger angular fragments are fine-grained quartz. The cementing material contains feldspar, feldspar intergrowths, and quartz. Several thin sections show rectangular and cubic crystals of quartz with corroded edges characteristic of alpha-after-beta quartz. Minor amounts of pyroxene are present. Secondary minerals include pyrite, which is altering to limonite, and calcite, which is often rimmed with chlorite.

The Bannock volcanic formation was first defined by A. L. Ander-

[1] "Notes on the Fort Hall Mining District, Utah," *U.S. Geol. Surv. Bull. 340* (1908), pp. 178–79.

son and included not only the lavas, tuffs, and breccias but also the overlying

> thin beds of impure limestone, calcareous shales, sandstone, quartzite, and conglomerate, measuring more than 1,200 feet thick. The base of the series is here unexposed, and the top has been taken to include the shale beneath the Black Rock limestone.[2]

He further states:

> Although this formation is considered tentatively as Lower Cambrian, the metamorphism which the series shows might suggest that the rocks are pre-Cambrian or Algonkian in age. The formation, however, apparently underlies the known Cambrian conformably, and it may represent the lowest part of the Cambrian, the mashing and shearing being accounted for by reason that the rocks are along the axis of an anticlinal fold. No fossils were found.

In this paper the sediments are treated as a separate formation because they occur as a unit and are much thicker than the volcanics. The Bannock volcanic formation is therefore redefined as a series of lavas, tuffs, and volcanic breccias of pre-Cambrian age which are exposed in the Bannock Range just east of Pocatello. Although the thickness of the formation cannot be given because its base is not exposed, there is a minimum of 400 feet.

POCATELLO FORMATION

Immediately overlying the ancient volcanic rocks is a thick series of unfossiliferous pre-Cambrian metamorphosed sediments, to which the name Pocatello formation is given. All the sediments which occur between the Bannock volcanic formation and the overlying Blackrock limestone are included. These were formerly a part of the Bannock volcanic formation of Anderson. The series shows considerable variations in thickness and distribution of the component sediments. The Pocatello is divided into two series: the lower is referred to as the tillite series and the upper as the varved slate series.

TILLITE SERIES

The lower part of the Pocatello formation includes silicified sandstones, slates, intraformational limestone conglomerate, thin-bedded metamorphosed limestones, argillites, and tillites. The estimated thickness is 1,100 feet.

[2] "Portland Cement Materials near Pocatello, Idaho," *Idaho Bur. Mines and Geol. Pamphlet 28* (1928), pp. 3–4.

This tillite series is exposed in four separate areas. One is along both sides of the ridge south of the bend in the Portneuf River. The second, and most extensive area, is along both sides of the ridge which rises to Chinks Peak. A third, but very small area, exists northeast of Pocatello, where sandstone alone is exposed. The fourth is in the Moonlight Creek region, where only sandstone and tillite are present.

The most important members of this lower series are the tillites, which occur in the upper part. South of the Portneuf River two zones of this material are interbedded with sandstones and limestones. The lower zone is 120 feet thick near the river and consists largely of boulders and cobbles of quartzite with relatively small amounts of matrix. Farther south the amount of matrix increases until the cobbles and pebbles are subordinate to and scattered through it. This is typical also of the higher zone south of the river and all the tillite north of the river. In addition to quartzite, this phase also contains pebbles and cobbles of gneiss and granular igneous rocks. The tillite covers much of the west slope of the ridge, rising to Chinks Peak, north of the river, and is exposed as scattered patches on the eastern slope. In the Moonlight Creek area the tillite rests in places directly on the Bannock volcanics. At no place north of the river was more than one zone of tillite located.

The tillite shows a complete lack of sorting. Most of it has a dark purplish-brown color, but this varies fron outcrop to outcrop. In the Moonlight Creek area the tillite is light brown, while on the southeast slope of Chinks Peak some of it has a light-green color. Many of the larger fragments are well rounded, but others are subangular or angular.

Studies of thin sections show the same lack of sorting in the rock fragments and mineral grains composing the matrix (Figs. 3 and 4). Most of the quartz and feldspar grains are quite angular and are scattered in a fine sericitized groundmass. Some sections show definite schistosity, while in others this is lacking.

VARVED SLATE SERIES

Overlying the tillite series are 350 feet of striped slates. In the upper part of the slates there are a few thin beds of sandstone which

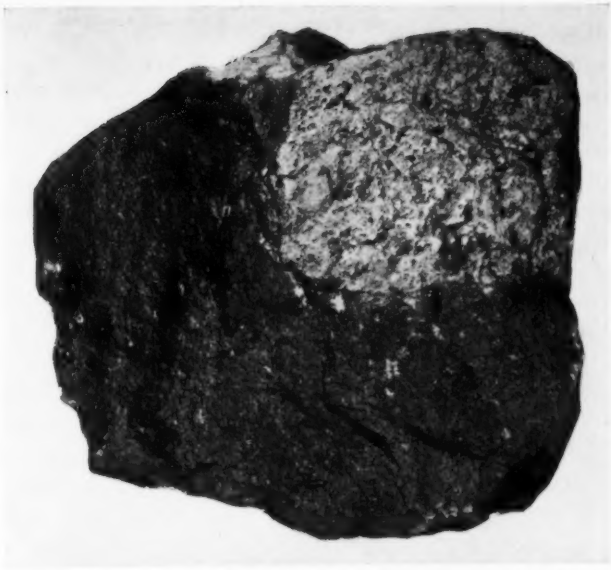

FIG. 3.—Photograph of a specimen of tillite from Chinks Peak. A pebble of gneiss is embedded in the dark matrix (7/10 natural size).

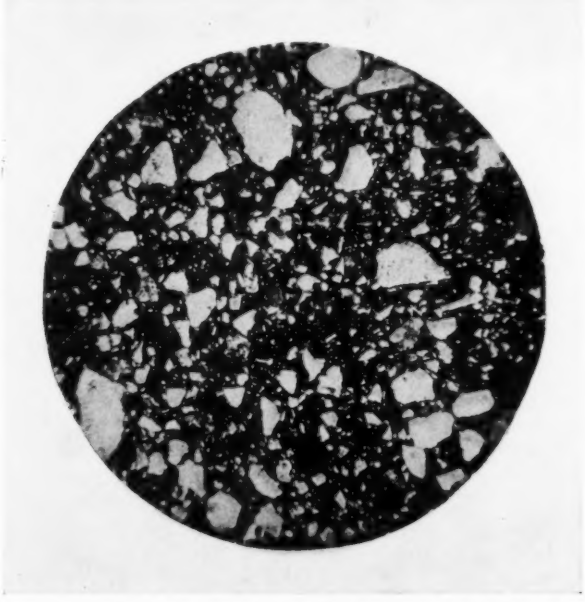

FIG. 4.—Photomicrograph of the matrix of tillite from Chinks Peak. The angular fragments are mostly quartz and feldspar (magnification × 20).

form a transition zone by intercalation with the slates and the overlying Blackrock limestone. The slate series exhibits varying degrees of metamorphism, including the phyllite stage. Cleavage is pronounced, and interpretations of its relation to bedding show many minor folds, some of which are overturned.

The fresh slate is typically light gray in color, but weathering produces various shades of brown and yellow. The rock shows alterna-

FIG. 5.—Photograph of a specimen of varved slate from Moonlight Creek area (4/5 natural size).

tion of dark and light bands, of which the lighter are usually the thicker (Fig. 5). The individual bands range in thickness from less than a millimeter to several centimeters, with an average of four or five millimeters. Thin-section studies show that coarser grains are in greater abundance in the light-colored layers. The above characteristics are typical of varved sediments, and, moreover, the intimate association of the slates with tillites points conclusively to a glacial origin.

BLACKROCK LIMESTONE

The Blackrock limestone overlies the Pocatello formation conformably and was named by Anderson[3] for its occurrence along the

[3] *Ibid.*, p. 4.

slopes of Blackrock Canyon, which[4] joins Portneuf Canyon from the north. This formation is typically a pure limestone, gray in color. Massive bedding is common, but in the lower part the bedding is much thinner. The maximum thickness of the limestone measured was 535 feet. While no fossils were found, small, deformed, and partly recrystallized oolite-like structures are abundant. These are characteristic of the Blackrock limestone wherever it outcrops.

There is a definite break at the top of the Blackrock, and it is overlain unconformably by a great thickness of Brigham quartzite. Evidence for this unconformity is based on anomalous strikes and dips in adjacent parts of the two formations. Further evidence is found in the greater metamorphism of the Blackrock limestone and underlying formations. The pre-Cambrian in this region is commonly sheared and brecciated, and thin-bedded members, such as the varved slates, exhibit well-developed fracture cleavage. Similar thin-bedded shales in the Brigham do not exhibit fracture cleavage. In addition, the Blackrock limestone is absent in places, and, where it is present, the thickness is very irregular. This would naturally be expected below an unconformity.

The overlying Brigham is unfossiliferous in the Pocatello area and almost completely so in other regions; consequently, its age is doubtful. Most writers, however, agree that it is either Lower or Middle Cambrian. Apparently, therefore, the unconformity beneath the Brigham marks the division between the pre-Cambrian and the Cambrian in the Pocatello area.

PRE-CAMBRIAN FORMATIONS OF THE WASATCH MOUNTAINS

It is interesting to find that the exposed pre-Cambrian formations of the Pocatello region show much similarity with equivalent formations in the Wasatch Mountains.

F. F. Hintze[5] first noted the tillites in the Cottonwood region of the Wasatch Mountains, twelve miles southeast of Salt Lake City.

[4] The spelling "Blackrock" rather than "Black Rock" is used, since the former appears on the United States Geological Survey topographic map of the Pocatello quadrangle.

[5] "A Contribution to the Geology of the Wasatch Mountains," *New York Acad. Sci. Annals*, Vol. XXIII (1913), pp. 99–100.

He described the tillite as a fine-grained rock having large and small boulders scattered through it. He believed the rock to be of glacial origin and the youngest member of the Algonkian series underlying the Cambrian unconformably.

Calkins[6] described tillites at the head of Superior Gulch in the same general region in the Wasatch Mountains. Here some of the scattered pebbles and boulders in the tillite consist of limestone and other sedimentary rocks.

Later, Eliot Blackwelder[7] listed the known and suspected occurrences of tillite in the Wasatch region and described some of them. In the Little Mountain district, about fourteen miles west of Ogden (Fig. 1), the tillites are underlain by green amygdaloidal lava and varved slates. In the Three Mile Canyon area, three miles southeast of Brigham, the tillite occurs between varved slates, the upper group of which grades upward into a great sequence of Lower and Middle Cambrian quartzites. Blackwelder also described the tillite of Big Cottonwood Canyon, first mentioned by Hintze. In the Rock Canyon area, twenty miles farther south, the tillite is separated from the overlying Cambrian quartzite by an apparent disconformity. Other localities mentioned are on the islands and along the shores of Great Salt Lake.

N. E. A. Hinds[8] discussed the pre-Cambrian–Cambrian contacts of the Wasatch region, stating:

> It appears that the tillite is interstratified with the pre-Cambrian well towards its top and that the Cambrian lies in places on the tillite and in others on quartzite lying stratigraphically above the tillite. The tillites and varved slates are pre-Cambrian, though, ... they are not Beltian.

The tillites and varved slates in the Pocatello region are very similar to those of the Wasatch region. In both regions they are near the top of the pre-Cambrian series, and correlation seems reasonably certain.

[6] B. S. Butler *et al.*, "The Ore Deposits of Utah," *U.S. Geol. Surv. Prof. Paper 111* (1920), p. 234.

[7] "An Ancient Glacial Formation in Utah," *Jour. Geol.*, Vol. XL (1932), pp. 289–304.

[8] "Contribution to the Pre-Cambrian Geology of Western North America," *Carnegie Inst. Wash. Pub. 463* (1936), p. 82.

This study extends the known areas of pre-Cambrian glaciation one hundred miles farther north than previously recognized. It is hoped that the descriptions of these pre-Cambrian formations at Pocatello, together with the probability of a recognizable unconformity above the glacial formations, may be helpful in determining the relations of the pre-Cambrian and Cambrian formations in other parts of western United States.

ACKNOWLEDGMENTS.—The help of Professor A. L. Anderson in outlining the problems of the area and the critical reading of the manuscript by Professors C. M. Nevin and C. W. Merriam is gratefully acknowledged.

REGIONAL CONTRASTS IN TORRENTIAL RAINFALLS HELP TO EXPLAIN REGIONAL CONTRASTS IN EROSION

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ABSTRACT

New data on rainfall intensity in the United States reveal notable regional contrasts in the amounts of rain received in short periods and in the frequency of large falls in short periods. In the eastern half of the United States there is a general southward increase in the amounts of rain received in short periods. The South receives about 50 per cent more water than the North in brief rains, but, in hard rains which last 8–24 hours, the Gulf coastal region receives more than twice as much rain as the northern part of the North. In the frequency of hard rains, the regional contrast is much greater, the deep South receiving large totals from ten to more than one hundred times as often as the North.

Extensive comparable data on the extent of soil erosion have resulted from the Soil Conservation Service surveys of the eastern half of the United States. Despite many local variations in the extent of erosion, correlated with soil, slope, and land use, these data reveal a general southward increase in erosion upon comparable areas. A detailed analysis of the regional erosional contrasts in Indiana here summarized is followed by a more general summary for the rest of eastern United States. It is concluded that part of the regional contrasts in erosion can be correlated with the frequency and intensity of hard torrential rains.

INTRODUCTION

That torrential rainfalls cause much more erosion than gentle rains is well known. Grove Karl Gilbert concluded long ago that the worst rainstorm of a century might cause more erosion than the combined total of all the other rains of the century. Yet there seems to be little realization that regional contrasts in torrential rainfalls help to explain various regional contrasts in erosion. This seems to be due chiefly to ignorance of regional contrasts in such rainfall but partly to inadequate knowledge of regional contrasts in erosion on comparable slopes, soils, and exposures and partly to the common assumption that the amount of erosion depends predominantly upon topography, materials, and vegetative cover.

RECENT WORK

Recently much American information on torrential rainfall has been compiled and analyzed. Also data as to extent of certain sorts

of erosion have been gathered and mapped. The chief purpose of this article is to present a summary of these recently available data and thereby to call attention to their utility in helping to understand erosion conditions.

An analysis of the amount and type of soil erosion in Indiana, as mapped in 1934 in some detail by the Soil Conservation Service, revealed a rather steady average increase southward in the severity of erosion on comparable slopes.[1] For example, about one-eighth of the area of the 17 counties north of latitude 41° has had considerable sheet erosion with considerable gullying; about one-sixth of the belt between the forty-first and the fortieth parallels of latitude (22 counties) is so affected; 43 per cent of the area of the 25 counties between the thirty-ninth and the fortieth parallels is similarly classified; 66 per cent of the land in the 24 counties south of the thirty-ninth parallel belongs in this classification. Several factors presumably have contributed to cause this southward average increase. Clearly, an important influence has been glaciation, for part of southern Indiana was not glaciated, and the remainder was last glaciated considerably longer ago than was northern Indiana. A detailed analysis of the amounts of erosion in the glacial zones (Late Wisconsin, Early Wisconsin, and Illinoian) and of the unglaciated region indicates clearly, however, that the regional contrasts in glaciation are inadequate to explain the regional contrasts in the amount of erosion. Similarly, the factors of regional variation in average slope, in soil, and in land-use, although significant, in part offset one another and clearly fail adequately to explain the regional erosional contrasts.

Hence various climatic influences of possible significance were considered, such as the annual amount of precipitation, the seasonal distribution of precipitation, and temperature contrasts, particularly in the duration of freezing temperatures and in the annual number of alternations above and below the freezing-point. Each of these climatic influences necessarily affects the amount of erosion, and together they help to explain the southward erosional increase

[1] S. S. Visher, "Regional Contrasts in Erosion in Indiana, with Especial Attention to the Climatic Factor in Causation," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), pp. 897–930.

recorded for Indiana. But, even with the help of the nonclimatic factors, they appear inadequate to explain the magnitude of the contrasts.

Next was considered a hitherto ignored aspect of the rainfall—its intensity or torrential character. An unusual combination of circumstances has produced in Indiana an exceptionally large regional contrast between the intensity of rainfall in the southern part of the state and that in the northern. Extreme southern Indiana has several times as many excessive or exceptionally intense rainfalls as does extreme northern Indiana, except during the summer, when runoff is least.[2] The regional contrast in rainfall intensity in Indiana during the cooler months is great enough, it is believed, to be highly significant. Consideration of the meteorological causes for the regional contrasts in rainfall intensity in Indiana leads to the conclusion that these regional contrasts have long existed. Hence, any regional contrast in erosion due to the intensity contrasts has been cumulative and is believed to be the factor causing most if not all such regional contrasts in the amount of erosion as are not adequately explained by the several environmental influences previously analyzed. Indeed, in the analysis here summarized, it was suggested that the preglacial ruggedness of southern Indiana which helped to stop glacial advance presumably was produced in considerable part by the more torrential rainfall during the cooler months. If so, local rainfall conditions supplemented local temperature conditions and various remote influences in determining the position of the glacial margin.

THE DISTRIBUTION OF TORRENTIAL RAINS IN THE EASTERN UNITED STATES

Partly as a result of discovering that there is a marked southward increase in Indiana in the torrential character of the cool-season rainfall, evidence was sought as to whether or not a similar increase continues southward for the whole eastern half of the United States. Three independent bodies of data bearing on this are now available. The oldest of these studies is by J. B. Kincer, of the United States

[2] Visher, "Rainfall-Intensity Contrasts in Indiana, Causes and Consequences," *Geog. Rev.*, Vol. XXVIII (1938), pp. 727–37.

Weather Bureau, who showed,[3] for example, that the frequency of days with rainfalls of more than 2 inches is more than four times as great in the South as in the North. Rains of 1 inch an hour are, he reported, more than five times as frequent in the South as in the North. Along most of the Gulf Coast, such rains occurred more than six times in 20 years, while they did not occur once near the Canadian border.

The greatest body of data on rainfall intensity was compiled relatively recently under the direction of David I. Yarnell, the senior drainage engineer of the United States Bureau of Agricultural Engineering. He analyzed the rainfall records for 208 weather-bureau stations which have recording rain gauges, and he presents in tables and in more than 70 maps the amounts of rainfall which should be expected in periods of various length.[4] In the United States, according to these official records, the amount of rain falling in periods of all the lengths studied (5 minutes to 24 hours) is greatest near the Gulf of Mexico and decreases rather steadily northward.

In some one hour of every decade, each part of the Gulf Coast receives a downpour of about 3 inches, each locality of the northern part of the East gets one rain of about half that total, and each locality in the West gets a fall of one-third that total. In some 2-hour period, 3 inches of rain fall in half of the years throughout the Gulf Coast, but such rains occur less than twice a century near the Canadian border. Every 25 years each part of the Gulf coastal zone receives at least one rain of more than 5 inches in 2 hours, while the hardest 2-hour rain of a quarter-century yields in the North less than 3 inches and, in part of it, less than 2 inches. Four consecutive hours of hard rain occur much more rarely in the North and West than in the South. Every 5 years each part of the Gulf Coast has at least one 4-hour rain of more than 4 inches. Such rain does not occur oftener than once a century throughout the Northeast. Of 8-hour and 16-hour rains, the regional contrasts are of similar proportions: the Gulf Coast receives more than twice as much rain in

[3] *Atlas of American Agriculture*, Part II: *Climate*, Sec. A: *Precipitation* (Washington: U.S. Dept. Agriculture, 1922).

[4] "Rainfall Intensity-Frequency Data," *Miscell. Publ. No. 204* (Washington: U.S. Dept. Argiculture, 1935).

the hardest rain of these durations as the Northeast and more than three times that of the West.

Figures 1 and 2, based on combinations of parts of Yarnell's maps, show conspicuously the sharp regional contrasts in eastern United States in the frequency of totals of brief rainfall sufficient to cause considerable erosion. Figure 1 shows that of rainfalls of 2 inches in 30 minutes, the Gulf Coast has more than twenty times as many as part of the Northeast (3 inches in 2 hours fall about fifty times as frequently in parts of the South as in a part of the extreme North). Similarly, Figure 2 shows that 8-hour rains of 5 inches or more occur at least once in 5 years along the Gulf but less than once a century in much of the North.

RAINFALLS OF 10 INCHES IN 24 HOURS

The sites of 293 rainfalls in excess of 10 inches in 24 consecutive hours at United States weather-bureau stations are shown on Figure 3. The three symbols classify the rains as to magnitude: the 7 large squares represent rainfalls of from 20 to 23.2 inches (at New Smyrna, Fla.); the 37 large dots represent rainfalls of 15–19.9 inches; the circles represent falls of from 10.0 to 14.9.

Figure 3 shows that the southern part of the South has had many rains in excess of 10 inches in 24 hours and that there is a rapid decline in numbers within 100 miles or so of the Coast, not only along the Gulf but along the Atlantic and Pacific. In the interior, there is a general progressive northward decline in the number of these very heavy rains. The chief exceptions are local increases in the southern Appalachians and near the Balcones Escarpment of the Texas Plateau.

Figure 3 shows that all the records of more than 20 inches of rain in 24 hours, nearly all those of 15–19.9 inches, and a large majority of those of 10–14.9 inches are in the southeastern quarter of the United States. An analysis of all the rains of these magnitudes recorded during a recent 10-year period reveals that the deep South (the Gulf states plus Georgia and South Carolina) had 75 of these records, the upper South (from Oklahoma to Maryland) had 8, the North 4, and the West 1. In proportion to area, the deep South had in that decade about twelve times as many official records of rains

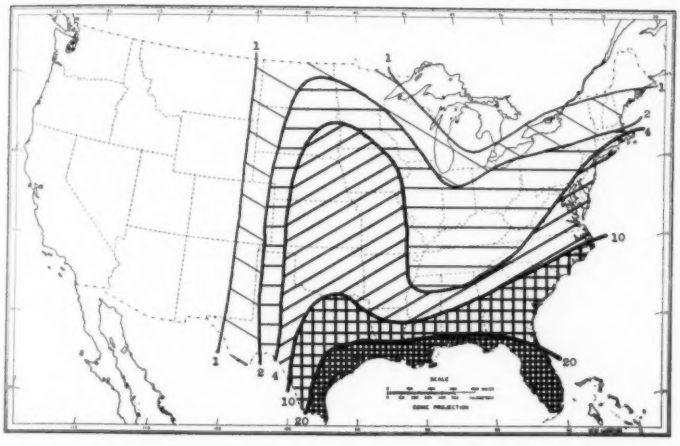

FIG. 1.—Times per century that rainfalls of 2 inches occur in 30 minutes

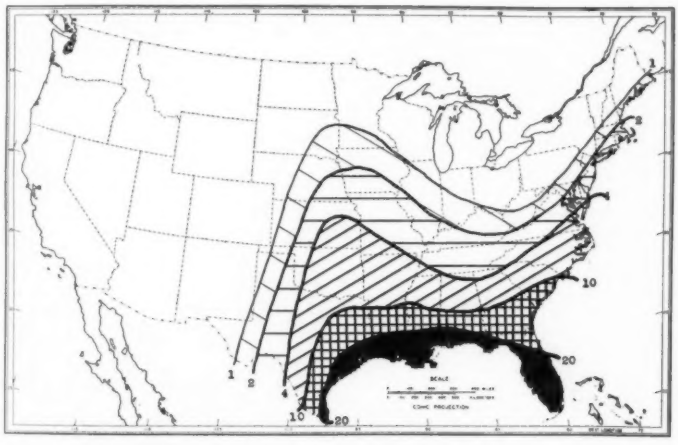

FIG. 2.—Times per century that 5 inches of rain falls in 8 hours

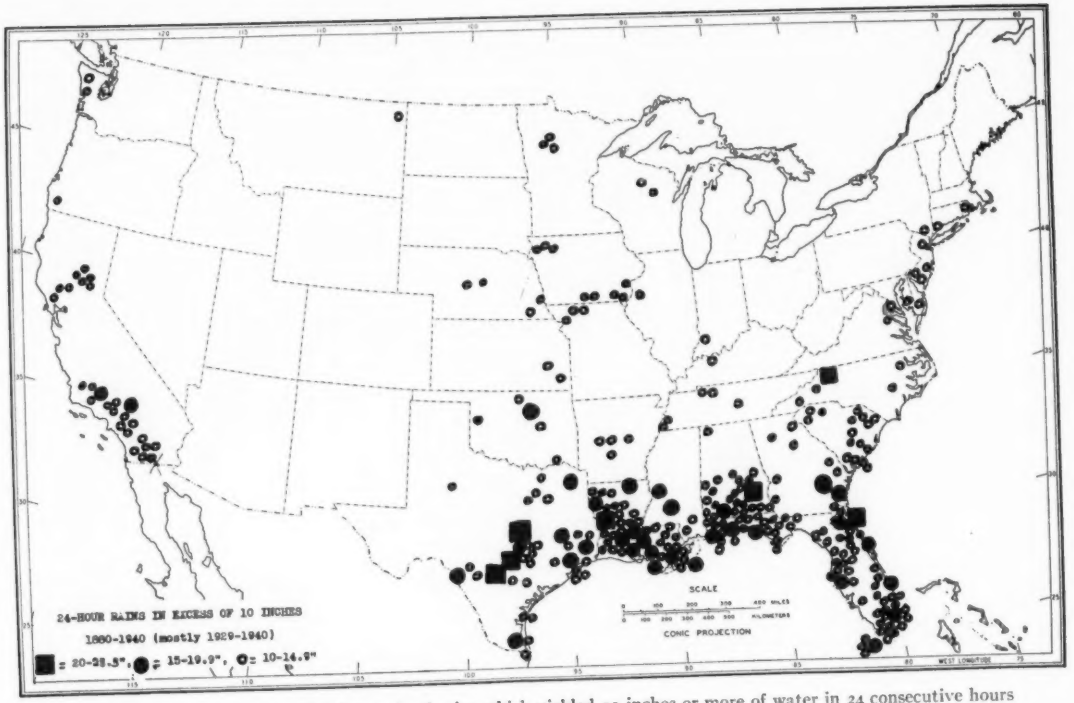

FIG. 3.—The sites of 293 official records of rains which yielded 10 inches or more of water in 24 consecutive hours

of more than 10 inches in 24 hours as did the upper South and more than one hundred times as many as did the 21 states of the North.

Among the causes for these regional contrasts in rainfall intensity are surely the three following: (1) Tropical cyclones, including moderate disturbances as well as hurricanes, cause a considerable share of the 24-hour rainfall records; they decrease in strength soon after coming upon the land.[5] (2) Thunderstorms are more than twice as numerous in the South as in the North,[6] and, as many of them migrate more slowly, they often yield more rain to a given locality. (3) The greater solar heating and the more abundant moisture supply near the Gulf also help to explain the northward decline in the frequency and intensity of exceptionally hard rains.

SOME EROSIONAL RESULTS OF EXCEPTIONALLY HEAVY RAINS

Exceptionally heavy rainfalls, such as 5 inches in a few hours or 10 inches in 24 hours, necessarily cause much runoff or flooding or both. Several sorts of damage are done, some of which have been discussed elsewhere with examples.[7] The erosional effects of such excessive rainfalls vary, of course, with the slope, soil, vegetative cover, tillage, and various other conditions.

It has been known for some time that soil erosion has been especially severe in the southeastern states. Official maps, for example Figures 4 and 5, show that, excepting Florida and the low-lying land along the Gulf and Atlantic coasts, fully four-fifths of the South has widespread, either "serious" or "harmful" erosion. By contrast, less than one-third of the North is classified in either of these categories. In the South, more than 40 million acres of formerly cultivated land already have been abandoned as a result of serious erosion, and an even larger area, presumably, will soon be abandoned. In the North, the formerly cultivated area which has been

[5] Visher, "Frequencies of Tropical Cyclones, Especially Those of Minor Intensity," *Monthly Weather Rev.*, Vol. LVIII (1930), pp. 62–69; "Effects of Tropical Cyclones upon the Weather of Middle States," *Geog. Rev.*, Vol. XV (1925), pp. 106–14.

[6] W. H. Alexander, "The Distribution of Thunderstorms in the United States," *Monthly Weather Rev.*, Vol. LXIII (1935), pp. 157–58.

[7] Visher, "Torrential Rains as a Serious Handicap in the South," *Geog. Rev.*, Vol. XXXI (1941), pp. 644–52.

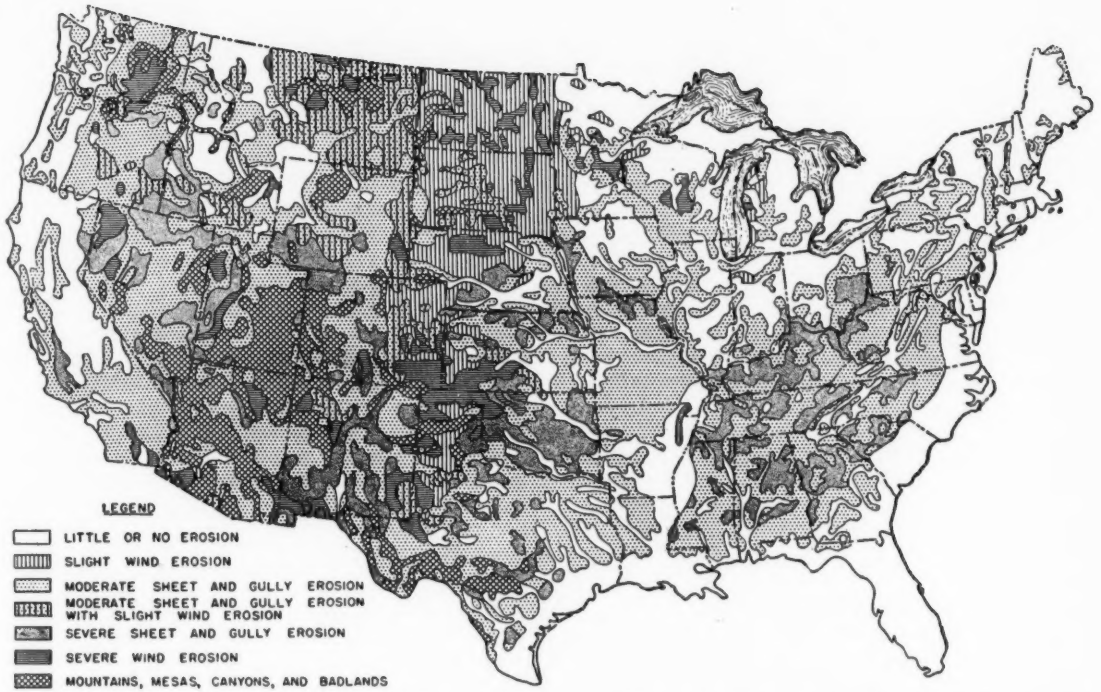
LEGEND
LITTLE OR NO EROSION
SLIGHT WIND EROSION
MODERATE SHEET AND GULLY EROSION
MODERATE SHEET AND GULLY EROSION WITH SLIGHT WIND EROSION
SEVERE SHEET AND GULLY EROSION
SEVERE WIND EROSION
MOUNTAINS, MESAS, CANYONS, AND BADLANDS

FIG. 4.—Principal areas of erosion in the United States, comprising 25 per cent or more of the land, affected as indicated. (Soil Conservation Service.)

abandoned because of soil erosion is relatively much smaller than in the South.

Although Figures 4 and 5 show that in a considerable share of the South less than 25 per cent of each square mile has been badly damaged by erosion, these areas are almost all restricted to the low

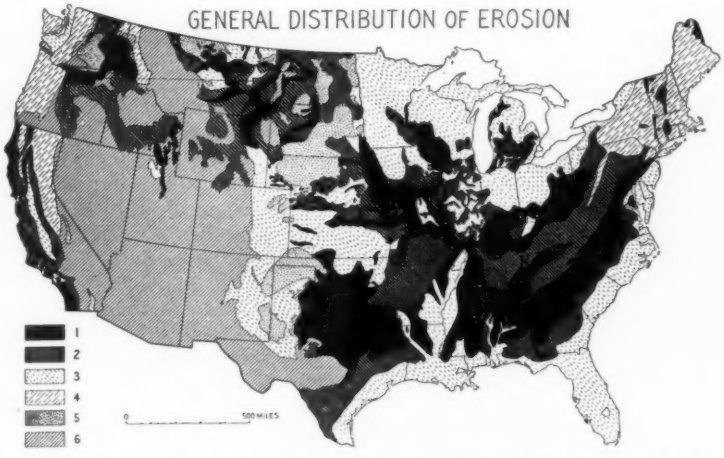

FIG. 5.—Degree of soil erosion. The maximum erosion by water, in the form of sheet erosion and gullying, has taken place in areas 1 and 2, where respectively serious and harmful erosion is widespread over cultivated and overgrazed areas (*Science Advisory Board Report* [1935]).

flat land bordering the coast or in the Mississippi Delta. But within such areas any land which has appreciable slope is eroded badly. There is no question that erosion upon comparable slopes and soils is decidedly more rapid in the South than in the North. This is only partly due to differences in land use or in temperature conditions, such as the duration of snow-covered and of frozen ground, or in annual and seasonal distribution of the rainfall. Obviously much of it is due to the regional differences in the frequency of exceptionally hard rains and their magnitude.

Conservation Service.)

REVIEWS

The New Systematics. Edited by JULIAN HUXLEY. Oxford: Clarendon Press, 1940. Pp. 583. $6.00.

This is a somewhat belated review of a publication which has attracted a great deal of attention in general biological circles but which unfortunately has apparently been missed by practically all American paleontologists and historical geologists, despite the rich significance of certain portions of the work for all men in those fields. In June, 1937, a group of the leading British cytologists, ecologists, and geneticists met at the headquarters of the Linnean Society at London and established an Association for the Study of Systematics in Relation to General Biology under the leadership of Julian Huxley. The association hoped to bring together a large group of biologists to study the question of how the recent progress in the ramifying branches of general biology could be employed to establish taxonomy on a somewhat more modern basis and, further, to discover how taxonomy might well be developed so as to further rather than impede future biological advances.

A number of the opinions expressed by the members of the association are neither new nor novel, for they have been prevalent for some years in Europe although little discussion of them has appeared in North American literature. Nevertheless, some biologists consider the very founding of the association to be an important milestone in the history of biology, for it represents the first organized attempt to depart from some of the antiquated viewpoints of most of the "classical" taxonomists. Dr. Leon J. Cole, University of Wisconsin geneticist, has already pointed out that the International Commissions on Nomenclature in both zoölogy and botany could help stabilize taxonomic problems if only they had more arbitrary powers in dealing with the many cases that come before them. He and many others feel that there is real danger that the rules of nomenclature will become inflexible and outmoded unless ample provision is made for modernization. Thus, although it is recognized that classical taxonomy should exert a conservative influence, it must nevertheless be prepared to take full cognizance of the amazing advances in biological knowledge. *The New Systematics*, which *in toto* represents a far from con-

servative viewpoint, has been written by twenty-two specialists, most of whom are British, but the author list reveals a minor representation from Germany, New Zealand, Russia, and the United States. Naturally, not all of the chapters have equal significance for the paleontologist, but Huxley's Introduction and Arkell and Moy-Thomas' chapter on "Paleontology and the Taxonomic Problem" should be required reading for all those in any way interested in the life of the past. In addition, Timofeeff-Ressovsky's section on "Mutations and Geographical Variations," Sewall Wright's contribution on "Statistical Consequences of Mendelian Heredity," Lancelot Hogben's section on "Problems of the Origin of Species," Gilmour's "Taxonomy and Philosophy," and Ford's "Polymorphism and Taxonomy" represent discussions which certainly should be considered something more than optional reading for the progressive paleontologist.

As would be expected, the authors differ in some cases rather sharply among themselves not only on the question of what is a species but on the problem of the higher taxonomic units as well. Naturally, some are of the opinion that the species is a more distinct and valid unit than the genus or any other higher classificatory rank, but some insist on the old concept that many evolutionary phenomena are better understood in the terms of the higher categories than when studied at the level of the species. Arkell and Moy-Thomas express the opinion that all the larger divisions of the classification should fit into a uniform scale of values, and they protest against the indiscriminate splitting of old genera. Huxley and Thorpe also join in condemning the growing concept of the monotypic genus.

As is to be expected, a number of taxonomists are beginning to advocate the dropping of the phylogenetic bases for taxonomy, but it must be remembered that both the practice and the theory of taxonomy in the fields of botany and zoölogy, as well as paleontology, have made their greatest forward steps only when they became inextricably associated with the theory of evolution itself. Naturally, taxonomy will advance in the future by becoming more involved in and more closely associated with genetics, physiology, ecology, embryology, and even with statistics and paleontology.

This reviewer agrees with Alfred Emerson, University of Chicago zoölogist, who has also commented on *The New Systematics*, that Huxley and Timofeeff-Ressovsky are not entirely correct in believing that paleontology, owing to the nature of its data, can only yield information concerning the course of evolution, not concerning its mechanism. Paleontology pro-

vides, or could provide, all sorts of data which would either refute or confirm theories of causation. Even some modern experiments in biology are not a great deal more helpful. Paleontology can yield much information concerning ancient as well as modern geographical isolation and its effect. Paleontology can show in greater detail than any modern study the ebb and flow of faunas and floras under competitive circumstances. Paleontological studies further supply important information on convergence and radiation which could never be ascertained thoroughly from the study of the living end products. It is perfectly obvious that a modern organism cannot be entirely understood solely through a study of relationships within and without its organic whole. The influences of countless past forces, physical and organic, have written an indelible, though possibly a difficultly read, record on the living organism—a record which, it may be said, is more likely to be deciphered by the paleontologist than by the average biologist. Moreover, paleontological studies provide some knowledge of the time factors involved—factors which many, but happily not all, zoölogists not only do not take into consideration but do not even completely comprehend.

Naturally, this reviewer also agrees wholeheartedly with Emerson's critical comment of certain ideas presented in this symposium:

> When the series of correlated facts are too meagre to form the basis for a convincing phylogeny, tentative working hypotheses may be substituted temporarily awaiting the accumulation of more data. If the data are so meagre that even a working hypothesis of phylogenetic relationship is not possible, some form of artificial arrangement may be substituted without taxonomic implications such as has recently been suggested. . . . . ["Utilitarian Classification for Fragmentary Fossils," *Jour. Geol.*, Vol. XLVI (1938), pp. 975–84.] If other valid biological principles form the pattern of correlation such as factors in the ecological habitat, the classification may follow another nomenclature which runs across but does not interfere or confuse the taxonomic and phylogenetic nomenclature. Polyphyletic groups are thus broken up in taxonomic classification but are often maintained in ecological classification.

If the average paleontologist is, as may well be surmised, somewhat similar to the reviewer in his deficiencies in the biological sciences, he is likely to find some sections of *The New Systematics* far from "light summer fiction." But all paleontologists, whether they came into the field through the biological or the geological door, will profit from a careful study of the concepts presented by the outstanding group of collaborators who made this volume a possibility.

CAREY CRONEIS

Wissenschaftliche Ergebnisse der Niederländischen Expeditionen in den Karakorum und die Angrenzenden Gebiete 1922, 1925, 1929–30 und 1935 herausgegeben von Dr. Ph. C. Visser und Jenny Visser-Hooft, Band III, Fas. 1: "Geologie." By RUDOLF WYSS, with parts by HANS RENZ and MANFRED REICHEL. Leiden: E. J. Brill, 1940. Pp. x+458; pls. 24; maps 3, fossil table. 40 guilders.

Following as it does the reports of the Italian expedition to the Karakorum ranges under De Filippi and the Trinkler expedition to Central Asia, the present volume has more than the usual interest of a regional study. The glaciology of the area was described in a previous volume, and this is the first fascicle of the geological volume. The first half of the work is devoted to description of the fossils by H. Renz of the University of Bern, with a section on the fusulinids by M. Reichel of the University of Basel. Unfortunately, it was not found possible to unite the faunal discussion of the collections made in 1929–30 with that of the collections of 1935. This fact introduces a certain amount of duplication and confusion which is not entirely removed by a short résumé of the ages and localities of the two groups of collections by R. Wyss (pp. 271–93).

The Paleozoic faunas consist of two Middle Devonian species, ten Lower Carboniferous species, and a large Permo-Carboniferous and Permian faunal assemblage. The higher rocks and faunas are assigned Lower Uralian, Upper Uralian, Lower Artinskian, and Upper Artinskian ages. The Lower Uralian beds yield twenty-two species, nearly all identified with species of the Eurasian Permo–Carboniferous. The Upper Uralian contains *Triticites*, *Schwagerina*, and *Parafusulina*, and a large Metazoan fauna similar to that of the Lower Uralian. The Lower Artinskian contains a variety of *Parafusulina* earlier described by Merla from a pebble. The Upper Artinskian yields a large and varied fauna consisting of *Doliolina*, *Schubertella*, *Neofusulinella*, *Parafusulina*, *Yangchienia*, many brachiopod species, and a small number of other invertebrates. No correlations are attempted, and the evidence for the coexistence of species found in rocks of widely differing age elsewhere is not convincing. The lists contain such names as *Spiriferina cristata octoplicata*, *Echinoconchus punctatus*, *Productus semireticulatus*, *Derbyia senilis*, *Athyris planosulcata*, and *Conocardium uralicum*, all of which are out of place in Permian rocks. American paleontologists will be loath to follow Renz in his identification of *Meekella striatocostata* and *Ambocoelia planoconvexa* in the Asiatic Upper Artinskian. New are three species and four varieties of fusulinids, sixteen species and varieties of brachiopods, two species of lamellibranchs, three of gastropods, and one "Orthoceras."

The Mesozoic faunas are all of few species but represent many faunal stages. All of the Mesozoic localities are in the Aghil Mountains, northeast of the Karakorum chain. Three Triassic faunal zones are recognized, the middle one characterized by the discoid hydractinian *Heterastridium*. Eight Jurassic faunal zones are differentiated, of which a Middle and an Upper Dogger zone yield abundant ammonites. The presence of an Upper Cretaceous horizon is indicated by the occurrence of *Exogyra conica*.

The fossil descriptions are thorough and the plates are of good quality. Stratigraphic information is sparse, and it is to be hoped that this lack will be remedied in a future fascicle.

The second section of the fascicle is "Petrography," by R. Wyss. The bulk of the section consists of detailed descriptions of the petrographic characters of rock specimens collected from scattered localities. In the Karakorum the principal igneous rocks are pre-Permian granite, diorite, and gabbro which intrude earlier metamorphics and which are overlain in places by post-Senonian volcanics. In the K'un-lun Range the granite is probably Devonian, and there are varied metamorphics. A few specimens from the Aghil Mountains and from the western part of the Himalayas are described.

The present work adds much to our knowledge of the geology of this remote region. A necessary work for the future is a volume correlating the results of the De Filippi, the Trinkler, and the various Geological Survey of India expeditions with those of the Netherlands expedition.

CARL C. BRANSON

Earth Sciences. By J HARLEN BRETZ. New York: John Wiley & Sons, Inc., 1940. Pp. x+260; figs. 123. $1.75.

It is not an easy task to write a book of two-hundred and sixty pages on the earth sciences for the college student and intelligent layman which is adequate in scope, readable, and yet reflecting a substantial spirit of scholarly inquiry. In this survey volume Bretz has achieved a result characterized by vigor of expression and scientific attitude. To this reviewer these are the book's outstanding virtues—no mean virtues considering the elementary purposes for which it was written. Part of the Bretzian style is to carry on a *sotto-voce* conversation with the reader by means of footnotes, parenthetical remarks, and provocative figure captions. Stimulating, here and there amusing, in some cases superfluous, these conversational "asides" do not mask, in fact they emphasize, the fundamentally sound scientific philosophy which is guiding the reader to an understanding of terrestrial environment.

Selection of material for a volume of this size was inevitable. The omissions are therefore conspicuous and for some teachers will undoubtedly raise questions regarding the value of the book as a text. For example, there is no mention of metamorphism beyond a scant reference to the contact variety. "The Earth's History," in fourteen pages, develops the fundamental principles of order of superposition and the repeating, rhythmic pattern of diastrophism, but the great dependence of the stream of evolving life on geographic change is largely omitted. On the other hand, there are included sections on the ocean, the atmosphere, and map projections. The chapter, "Effects of Unequal Hardness of Rocks on Streams," is particularly well done and should be successful in developing for the layman a basis for the understanding of landscape. And throughout the volume drawings by Rudolf Bretz point the descriptions with diagrammatic clarity. Otherwise the format is that of a conventional textbook.

To the reviewer Bretz's discussion of weather forecasting according to the classical cyclonic method is a disappointment. Certainly the difficulties of an elementary statement of air-mass analysis are not insurmountable. One might also take exception to the treatment of several other topics. For example, the origin of mountains and continents and oceans is attributed solely to wedge-diastrophism. But one must remember that controversial subjects cannot be adequately covered in a book of designedly limited scope. And in general the spirit of the writing is such as to make it clear that the earth sciences, while having a well-developed scientific approach, are replete with unsolved problems.

This is but to repeat what the reviewer said at the beginning: a sustained fluency and a vigorous scientific attitude are the book's commanding virtues, and for these reasons the volume deserves careful consideration by teachers of survey courses and by those who are called on to recommend reading to the layman.

A. C. SWINNERTON

Some Fossil Plant Types of Illinois. By RAYMOND E. JANSSEN. Springfield: Illinois State Museum, Scientific Papers, Vol. I, 1940. Pp. 124; pls. 28. $1.25.

Lesquereux was the first to study the paleobotany of Illinois, and in the 1860's he established 109 species of Carboniferous plants from this state. Janssen has revised the taxonomy and determined the validity of Lesquereux's identifications. Although all of the type specimens were supposed to have been deposited with the State Museum, only 59 were

found; these have been considered in this review. Eighteen species remain valid, but 10 of these are referred to different genera. In addition 10 new species from the Mazon Creek have been described.

The specimens have all been photographed and with few exceptions (where too large for a single plate) have been reproduced natural size. Some of the illustrations, however, are not very definitive because of the poor preservation of the material.

This is the first of a series of volumes planned to deal with the collections of the State Museum. They are intended for the specialist rather than the general public.

C. W. STERNBERG

Geology of the Presidential Range. By RICHARD P. GOLDTHWAIT. (Bull. 1.) New Hampshire Academy of Science, 1940. Pp. 43; figs. 22.

This is an excellent geological account of one of the well-known scenic areas of this country. It is "popular" geology, written by a competent geologist, and therefore not suffering from the inaccuracies so common in this type of publication. Everything is explained in clear, simple language, and the features are well illustrated (chiefly by aerial photographs); it is a pleasure to read.

The Presidential Range is carved from a thick mass of crumpled rock composed chiefly of mica schists and gneisses which are altered sediments of Devonian age. Below these are still older beds of black amphibolite schists which crop out along the northern edge of the Presidential Range. The only other common rocks are granites intruding the sediments. The oldest erosional surface that can be recognized is the Presidential Upland, which cannot be certainly dated but which was probably an area of rolling hills near sea-level at some time between the early Cretaceous and Miocene. This surface has been carved by later streams, by mountain glaciers, and smoothed by the continental ice sheet in late Wisconsin time. The intense frost action on the mountain tops is discussed in some detail.

C. W. STERNBERG